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Flight Evaluation of LORAN-C in the State of Vermont

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Flight Evaluation of Loran-C in the State of Vermont

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Final Report

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16. Abstract

The Transportation Systems Center, Langley Research Center, the Federal Aviation Administration, and the Agency of Transportation, State of Vermont conducted a program sponsored by the Research and Special Programs Administration of the Department of Transportation to evaluate LORAN-C as a supplement to existing navigation aids for general aviation aircraft, particularly in mountainous regions of the United States and where VOR coverage is limited.

This report highlights results obtained in completing 215 non-precision approaches and 104 flights. The flights, initiated in the summer months, extend through four seasons and practically all weather conditions typical of northeastern U.S. operations have been experienced.

Assessment of all the data available indicates that LORAN-C signals are suitable as a means of navigation during enroute, terminal and non-precision approach operations and the performance exceeds the minimum accuracy criteria specified by the FAA Advisory Circular 90-45A, "Approval of Area Navigation Systems for Use in the U.S. National Airspace System.

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PREFACE

Radionavigation is required to support movement of resources, raw materials, manufactured goods and people in the processes of economy and trade and to insure safety of life and property in commercial land, sea and air transportation systems. The Department of Transportation is the primary Government provider of aids to navigation used by the civil community. The Research and Special Programs Administration plans, directs, and sponsors radionavigation research, engineering, and development activities to improve existing operations or to assess future system alternatives. The LORAN-C FLIGHT EXPERIMENTS program, documented in this report, was designed to determine the suitability of LORAN-C for enroute and terminal navigation and for non-precision approaches at small airports in mountainous terrain.

The success of the program is a result of the combined efforts of three federal government organizations (DOT's RSPA, FAA and NASA) and one state organization (Vermont's Agency of Transportation). This report was written under the direction of the principal author and project engineer Franklin D. MacKenzie, assisted by Carroll D. Lytle of the Langley Research Center. Major editorial contributions throughout the report were made by William B. Polhemus, Polhemus Associates, Inc. The section on flight procedural test results was written by William C. Hoffman and Bruce C. Lubow of Flight Transportation Associates; the section on ground based LORAN-C signal monitoring results was written by Julian L. Center and Krishnan Natarajan of JAYCOR.

The technical review team included George H. Quinn of the Federal Aviation Administration, Walter M. Hollister, Flight Transportation Associates, Bahar J. Uttan of JAYCOR, Paul D. Abramson and Maurice J. Moroney, Jr. of the Transportation Systems Center, and George C. Combes of the Vermont Agency of Transportation.

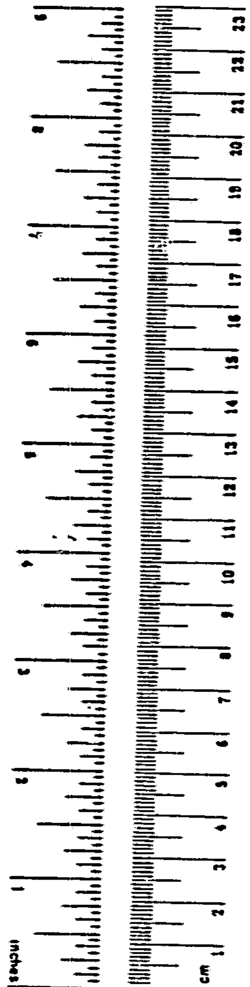
Sections 1, 2, and 3 constitute the final report. The first contains introductory material, and the second the test results. This is followed by a summary of the significant results of the test program. Following the main body of the report are three appendices, going into greater detail on LORAN-C performance characteristics, the results of an FAA sponsored LORAN-C receiver study and an analysis of two of the 104 flights completed during the test program. Also included is a List of Abbreviations Used.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

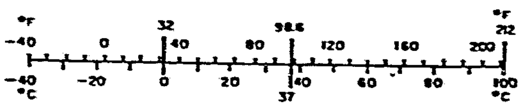
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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List of Abbreviations

ATC	Air Traffic Control
ATE	Along Track Error
BTV	Burlington International Airport
CAB	Civil Aeronautics Board
CDI	Course Deviation Indicator
CDU	Control and Display Unit
CTE	Cross Track Error
CRT	Cathode Ray Tube
db	decible
DME	Distance Measuring Equipment
DOT	Department of Transportation
drms	distance root mean square
ECD	Envelope-to-Cycle Difference
EM	Electromagnetic
FAA	Federal Aviation Administration
FBO	Fixed Base Operator
FRP	Federal Radionavigation Plan
FSK	Frequency Shift Keyed
ft	feet
FTE	Flight Technical Error
GA	General Aviation
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GRI	Group Repetition Interval
GMT	Greenwick Mean Time
IFR	Instrument Flight Rules
ILS	Instrument Landing System
kHz	kiloHertz
LDA	Localizer Type Directional Aid
LF	Low Frequency
L/L	Latitude/Longitude
LOP	Line of position
LRC	Langley Research Center
MAP	Missed Approach Point
MDA	Minimum Descent Altitudes
MPV	Montpielier Airport
MVL	Morrisville Airport
NDB	Non-directional beacon
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAVAIDS	Navigation aids
NERO	New England Regional Office
nm	nautical miles
PLC	Power Line Carrier
RAPCON	Radio Approach Control
RAPPS	Remote Airborne Precision Positioning System
RCU	Receiver and Computer Unit
RF	Radio Frequency
RNAV	Area Navigation
RPM	Revolutions Per Minute
RSPA	Research and Special Programs Administration

rss	root sum square
RW	Runway
SAM	Service Area Monitor
SID	Standard Instrument Departure
SNA	Signal to Noise Ratio for Caribou (Station A)
SNB	Signal to Noise Ratio for Nantucket (Station B)
SNR	Signal to Noise Ratio
SRDS	Systems Research and Development Service
STAR	Standard Terminal Arrival Route
STC	Supplemental Type Certificate
TD	Time Difference
TDA	Time Difference for Station A
TDB	Time Difference for Station B
TDC	Time Difference for Station C
TERPS	Terminal Instrument Procedures
TSAT	Total System Along Track
TSC	Transportation Systems Center
TSCT	Total System Cross Track
USCG	United States Coast Guard
UHF	Ultra High Frequency
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Very High Frequency Omnidirectional Range
WP	Waypoint

EXECUTIVE SUMMARY

Introduction

The use of a LORAN-C navigator as a navigation system suitable for Area Navigation (RNAV) in the National Airspace System requires that several accuracy and operational questions be answered. The U.S. Department of Transportation (DOT), the National Aeronautics and Space Administration (NASA) and the State of Vermont developed a cooperative research program to evaluate the feasibility of using LORAN-C to satisfy enroute, terminal and non-precision approach accuracy requirements.

The State of Vermont requested this program in an attempt to find a relatively low cost technique to allow aircraft to operate into and out of twenty-five aviation facilities situated in mountainous terrain. The geographical environment, rapid changes in weather, seasonal variations, and limited number and capability of navigational facilities characteristic of Vermont's navigation problem are shared by other regions of the U.S. Therefore, it should be possible to generalize results obtained in Vermont to these other regions.

Scope Of Tests

The overall goal of this test program was to generate a comprehensive data base of technical and operational experience with the LORAN-C navigator as an air navigation system. Specific objectives of the program are:

1. Document the acheivable accuracy of the LORAN-C navigator as an RNAV system, for enroute, terminal and for non-precision approaches to remote airports in the mountainous Vermont terrain.

2. Evaluate the operational and procedural requirements for routine use of the navigator in this environment.

3. Measure LORAN-C signal characteristics at four ground monitoring sites in Vermont over an 18 month period to determine electromagnetic compatibility, predictability, temporal stability and the availability of the signal for airborne navigation.

4. Obtain FAA approval by Supplemental Type Certification (STC) for the LORAN-C equipment installation in the Twin Bonanza.

The flight program was designed to determine the suitability of using a general aviation class, off-the-shelf, LORAN-C navigator as a means of navigating during enroute, terminal and non-precision approach operations. Minimum accuracy criteria established for the evaluation program are those specified by FAA Advisory Circular 90-45A "Approval of Area Navigation Systems for Use in the U.S. National Airspace System".

Summary Of Activities

The DOT/NASA/State of Vermont LORAN-C experimental team has completed 104 successful flights and 226 airborne hours of operation. The Twin Bonanza aircraft was used in the evaluation of FAA-designed non-precision LORAN-C approaches to nine runways at five airports. Terminal Area and Enroute RNAV procedures and navigation accuracies were evaluated. A cross section of general aviation pilots participated in the evaluation as a means of assessing pilot reaction, workload and potential improvements. All reactions were supportive of the objectives of the program.

This report documents the results from the 104 flights completed during the flight test program. The number of operations during this period includes 215 approaches and 274 RNAV segments. The flights were conducted in both visual and instrument meteorological conditions; during daylight, at night and during twilight hours; using both the primary and alternate triads of the Northeast LORAN-C chain.

In addition, during the test period, four ground based monitor units acquired extensive data describing the LORAN-C signal characteristics. The number of days of accumulated data were:

Site 1.	Burlington Airport (NASA trailor)	168 days.
Site 2.	Burlington Airport (Air North Hanger)	193 days.
Site 3.	Rutland Airport	120 days.
Site 4.	Newport Airport	131 days.

Results and Conclusions

Measured performance was shown to exceed the minimum accuracy requirements specified for area navigation in the FAA Advisory Circular 90-45A for all phases of flight. The LORAN-C navigator system was found to be satisfactory for non-precision approaches (the most demanding of the accuracy requirements) at all test site airports once the runway threshold latitude and longitude coordinates were verified. It was also demonstrated with visual measurement that accuracy was further improved by inserting locally measured parallel offset values. All error sources were identified and measured. All of the error values were found to be much less than the displayed resolution in the LORAN-C navigator and did not warrent compensation when navigating using signals from the primary triad.

The evaluation of the operational and procedural requirements to use the system demonstrated a potential benefit for the air traffic control system and the general aviation user. Air traffic control would benefit from the capability of providing enroute-direct and traffic reliever routes; general aviation would benefit from shorter, more direct routing for approaches and departures.

The evaluation of the LORAN-C signal characteristics from the ground monitor sites demonstrated compatibility, stability and availability. The receivers were not effected by any noise sources found at medium

or small size airports in Vermont. The LORAN-C measurements demonstrated a long term stability (relative insensitivity to seasonal changes) of .06 nm peak-to-peak. Signal availability was determined to exceed 99%.

It was concluded that the LORAN-C transmitter station signals and the airborne navigator meet all relevant criteria for RNAV throughout the area of operation.

a. Enroute Accuracy Results

During the test period, 66 enroute segments were completed within the precision test range. A total of 29 flights were analyzed for compliance with the accuracy requirements of AC90-45A. In all error categories, the values were determined to be substantially less than the values stated in the advisory document. The mean total system cross track error plus two standard deviations about the mean value is 0.73 nm as compared with the AC90-45A performance requirement of 2.5nm. The major contribution to the error was the pilots ability to null the cross track deviation indicator.

b. Terminal Accuracy Results

One hundred five (105) terminal segments (25 flights) were flown on the precision test range. These segments were analyzed for compliance with the performance requirements in the advisory document. The mean total system cross track error plus two standard deviations about the mean value is 0.60 nm. The AC90-45A, minimum performance requirement is 1.5 nm. Again the major contributor to the error was the pilots ability to null the indicator.

c. Approach Accuracy Results

During the test period 76 approaches were flown on the precision test range. Scheduled non-precision approaches were made to 8 runways at 4 airports. Test data from the 31 flights were analyzed for compliance with the

requirements listed in the advisory document. The mean plus two standard deviations value of total system cross track error was 0.32 nm and is to be compared with the AC90-45A value of 0.6nm.

d. Approach Accuracy Results Using Parallel Offsets.

All of the visual estimations of cross track error reported for 272 approaches were less than the AC90-45A performance limit of 0.6 nm. Over half of the approaches were completed with an estimated cross track error between 0-150 feet and eighty percent of the approaches were completed with an observed cross track error measured at runway threshold of less than 300 feet.

e. Error Source Identification and Values

It was possible to identify the following sources of error and to determine their values.

The dynamic error in position due to the motion of the aircraft while collecting data was .02nm (122 feet). The mean error in the knowledge of transponder coordinates was determined to be in the same range (100 feet). This error was not caused by errors in the survey but by incorrect estimates of direction and distance in the occasional repositioning of the transponder.

The uncompensated portion of the velocity of propagation term in the navigator causes both TD values used for a fix to be a higher value in microseconds, 0.3 to 0.4 microseconds, than would be the case if the paths were entirely over sea water. The resulting latitude and longitude calculations were therefore more west and south of the true position (200 to 300 feet).

The temporal variation in TD value due to ground conductivety changes was determined to be .06nm (300 to 400 feet) peak-to-peak; the period of variation was one year.

All of the above error values were much less than the displayed resolution in the LORAN-C navigator and did not warrent compensation while navigating with signals from the primary triad. Navigation with the alternate triad

was acceptable (error values were less than those allowed in the advisory document) when the TDC-711 was provided a calibration value of 2nm south latitude and .30nm west longitude.

f. Operational Benefits

The operations in Vermont during the 18-months long flight program have indicated the possibility of providing additional departure and arrival paths, straight-in approaches, improved holding patterns, enroute-direct and traffic reliever routes which will increase the safety or efficiency of the National Airspace System. The ability to define impromptu fixes, fly direct to any given fix, and fly a parallel course, offset from the parent course by a specified amount, all enhance the performance of today's ATC system. Moreover, the LORAN-C RNAV capability will permit definition of more direct routes thereby shortening trip distance, saving fuel and reducing operating costs for general aviation users.

g. Ground-monitoring Results

All of the results derived from an analysis of the data gathered at the four ground stations were verified with analysis of airborne test data. It was concluded from the data analysis that LORAN-C reception in the Vermont electromagnetic environment can easily support uninterrupted operation while the aircraft is on the ground or at any altitude. The transmitter stations in the primary triad provide very high signal-to-noise ratios in Vermont. Two stations of the alternate triad provide high signal-to-noise ratios; the third station Carolina Beach provides an acceptable signal-to-noise ratio (greater than-10db) most of the time (89 percent). Temporal variations were decomposed into seasonal and diurnal subsets. There was such a large error margin between observed TD variations in Vermont and AC90-45A requirements that there was no difficulty in meeting accuracy requirements. By examing the ground data, airborne data and the U.S. Coast Guard chain logs for the test period it was concluded that the signal availability is significantly greater than 99 percent for the entire chain.

Summary

In all regimes and all error categories the LORAN-C system has demonstrated compliance with AC90-45A.

Enroute operations were within ±.73 nm of the desired track compared with the requirement of ±2.5 nm. Terminal operations were within ±.60 nm of the desired track compared to the AC90-45A requirement of ±1.5 nm and non-precision final approach operations were ±.32nm, also, within the AC 90-45A limit of ±0.6 nm for all approach operations.

Based on the analysis in this report the suitability of the LORAN-C navigation system in the current National Airspace System environment has been adequately demonstrated. No degradation in navigation accuracy or functional performance was observed using the LORAN-C navigation system when compared to the current VOR/DME system in the aircraft.

1. INTRODUCTION

1.1 BACKGROUND

In 1977 the Vermont Department of Aeronautics presented the Department of Transportation (DOT), Office of the Assistant Secretary for Research and Technology (forerunner of Research and Special Programs Administration (RSPA)) with an informal request for assistance in improving air access to the State's low altitude airspace and airports. At that time it was noted that the influx of new businesses to Vermont communities was creating a demand for improved airline, air taxi and business aircraft services which could not fully and efficiently be met in view of limitations in navigation and approach aids.

With the exception of the international airport at Burlington none of the state or privately-owned airports was equipped with either precision approach or terminal area radar service. While eight of the ten state airports do have Federal Aviation Administration (FAA)-approved non-precision instrument approaches only three include Localizers, the remaining five relying upon either Very High Frequency Omnidirectional Range (VOR) or Nondirectional Beacon (NDB) approaches. The result is an unsatisfactory history of cancellations or delays at all but Burlington. Even at Burlington weather conditions often force arriving traffic to use runways other than the Instrument Landing System (ILS)-serviced runway, in some cases requiring use of circling criteria with their attendant higher minima.

Low altitude enroute and terminal area operations are hindered by high terrain which interrupts line of sight signals from the FAA-provided VOR system; in fact, at only four airports can a pilot utilize VOR signals below about 3000 feet mean sea level.

In 1974 the State's Department of Aeronautics was made aware of the potential of LORAN-C to provide the navigation and guidance capability necessary for operation in the mountainous terrain. In support of Vermont's expressed interest, DOT/Coast Guard conducted a series of demonstration flights over a period of a week in a LORAN-C equipted C-130 aircraft. Low altitude enroute, terminal area and approach operations were

successfully demonstrated at a number of the mountain-bound airports. These activities ultimately led to development of a formal request from the State of Vermont to the DOT/Research and Special Programs Administration and to the Transportation System Center (TSC) for assistance in conducting an operationally and scientifically credible, extended evaluation of LORAN-C Area Navigation (RNAV) with a view to complementing the existing system of government-provided aids and procedures and to removing some of the present operating restrictions.

At present there are nineteen public-use airports within the State, one is owned and operated by the city of Burlington; ten are state-owned and maintained but operated by Fixed Based Operators (FBO's) through leasing arrangements; the remaining airports are privately owned. Two of the State-owned airports have been designated by the Civil Aeronautics Board (CAB) as "essential service*" airports.

Four of Vermont's airports are currently utilized by the scheduled airlines. Air taxi and business aircraft operations are conducted with growing frequency from almost all of the airports; however, boardings or number of operations are not at a level sufficient to meet DOT/FAA criteria for up-grading of facilities, with the exception of Burlington International Airport.

Recent developments in LORAN-C ground-based and airborne equipment could offer an opportunity to meet some of Vermont's operational and technical needs within a reasonable period of time and without requiring major capital expenditures.

*An aircarrier, under a contract with the CAB, provides an essential service airport with a specified minimum number of scheduled airline seats per week.

The aids to air navigation which are now in use by civil aviation have a history of reliability and simplicity of operation which are well earned and respected. Acceptance of LORAN-C RNAV by the general aviation community will depend to a considerable extent on its ability to demonstrate similar characteristics while at the same time offering significant advantages in performance or capabilities particularly appropriate to operation in the Vermont environment. Appendix A describes LORAN-C signal characteristics.

Improvements in signal strength and position fix accuracy which resulted from commissioning of the Seneca, NY transmitter and the Northeast LORAN-C chain now permit reception from four transmitters at all of Vermont's airports from ground-level to all operational altitudes, despite the presence of mountainous terrain, with a repeatable accuracy suitable for non-precision approaches to any runway, and for development of new departure flight paths at many airports. In addition, low altitude enroute navigation would be made less harzardous for both Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) traffic.

The current FAA program to develop a relatively low cost LORAN-C RNAV system is particularly timely as it will enable all categories of General Aviation (GA) to participate in the eventual benefits of LORAN-C. Appendix B presents applicable specifications of the low cost receiver study.

A major evaluation program was organized by TSC which brought together teams from the National Aeronuatics and Space Administration's (NASA) Langley Research Center (LRC), the FAA, and Vermont's Agency of Transportation. Together with these organizations, TSC developed test and management plans, measurement criteria, ground and airborne test instrumentation subsystems, data gathering and reduction strategies, and assigned responsibilities necessary to measure and document the capabilities and limitations of LORAN-C RNAV.

Considerable effort was expended from the outset to establish the actual performance of the ground reference system, the proper integration of the data gathering instrumentation, the time correlation of the inputs of all subsystems which could have an effect on the conclusions reached in the test, and requirements for the data reduction software at LRC.

In consequence a very demanding technical load was placed on NASA's scientific team both in the laboratory at Langley Research Center and at the test range at Wallops Island, VA which was carried out in a highly professional manner. A major consideration addressed by the engineering team was confirmation that all uncertainties in equipment behavior, (ground truth system operation, software, etc.) were eliminated prior to commencing the formal data gathering effort, a problem which has plagued previous LORAN-C RNAV test projects. More than 72 hours of flight time were expended in this area.

1.2 PROGRAM OVERVIEW

The principal objective of the Vermont LORAN-C RNAV program was to determine the functional, technical and operational suitability of the low frequency radio navigation aid to meet the needs of civil aviation in the Vermont environment. A necessary element of this determination was the acquisition of independently gathered ground and airborne measurements taken over an extended period of time so as to include, to the extent possible, all expected variations in natural physical phenomena commonly experienced in air operations and likely to affect signal propagation, airborne system performance, pilot workload or interaction with the Air Traffic Control (ATC) system.

The principal measurement tasks included:

1. Acquisition of a statistically significant number of quantitative and qualitative measurements of the airborne RNAV system's behavior.

2. Validation of system accuracy through use of a very precise (10 meters, 2 drms) ground-reference system.

3. Assessment of unique operational and procedural requirements with particular interest in identification of any which could adversely affect pilot workload, acceptance by the ATC system, or flight safety.

4. Accumulation of GA pilot system-acceptance data.

5. Acquisition of LORAN-C signal characteristic data at four ground facilities.

6. Compilation of an archive of meteorological data for the period of the evaluation program.

The airborne operations were planned to span a period of approximately 18 calendar months. Three separate but related flight evaluation programs were completed during the project. The first involved approximately 32 flight hours of accuracy testing by the FAA's Technical Center utilizing a Convair 580 aircraft equipped with two LORAN-C systems: a Teledyne Systems Company high-price-range TDL-424 unit and second a TDL-711 mid-price unit currently used for offshore operations by over 500 helicopters. Neither of these systems was instrumented to supply command guidance information to the aircraft pilot. The CV-580 flight program was under the direction of a FAA's Technical Center Project Engineer who also had responsibility for reporting, separatly the results of the FAA effort.

The second flight evaluation program, conducted under the direct supervision of the TSC Program Manager, utilized a twin-Beech E50 aircraft owned and operated by the State of Vermont. The E50 was equipped with a single Teledyne Systems Company TDL-711 unit and was scheduled to fly approximately 100 flights (totaling 200 hours), distributed across the following activities: equipment check out, training, acquisition of performance data, development and evaluation of procedures, determination of pilot workload and system acceptance, and identification of potential ATC interface problems. The TSC/Vermont flight test team successfully completed 104 flights and 226 hours of LORAN-C RNAV operation.

The LORAN-C RNAV system in the E50 was instrumented to provide command steering information to the pilot through a dedicated Course Deviation Indicator (CDI) and this configuration was regarded as the "primary mode" of operation.

The third flight evaluation activity was added to the project about halfway through the program. A Cessna 210 aircraft belonging to a local air taxi operator, The Airmaster, Inc., was equipped with a TDL-711 system. This aircraft was also equipped with a dedicated CDI on the pilot's instrument panel. The air taxi operator was requested to evaluate the system during its routine charter operations. Two of the operator's regular pilots were trained to use the equipment and were asked to keep notes on their experiences. A total of 450 hours of successful enroute LORAN-C RNAV evaluation was accomplished during an eight month period. The LORAN-C evaluation flights reduced expenditures for fuel and operating costs ranging from 7 to 16 percent, with an overall average of 6 percent.

In summary this report documents the results of more than 676 hours of successful airborne LORAN-C experience gained during the period July 1979 - March 1981.

1.3 PROJECT ORGANIZATION

Three federal government organizations (DOT's RSPA, FAA, and NASA) and one State organization (Vermont's Agency of Transportation) joined forces to plan and to successfully execute the LORAN-C evaluation program. Within the DOT the RSPA had overall program cognizance.

The Transportation System Center was designated by RSPA to assume responsibility for program management, design of experiments, provision of some of the ground and airborne equipment, basic field measurements, data analysis, industry briefings, public relations and preparation of reports.

The LRC of NASA designed, fabricated, installed and calibrated the successful data collection instrumentation installed in the Vermont Beech E50 aircraft and provided a second system in a ground-based instrumentation trailer situated throughout the program at the Burlington Airport (BTV). This latter unit was operated on-line continuously from July 1979 until November 1980. The airborne and ground-based data gathering installations included NASA-designed and fabricated microprocessors which controlled, formatted and recorded data on magnetic tape. Langley personnel also prepared software necessary to process and evaluate the information collected by the Beech aircraft and the instrumented trailer. LRC was a partner in evaluation of all data gathered by the Beech E50 aircraft.

The FAA participation in the program involved four of its organizations: the Systems Research and Development Service (SRDS); the FAA's Technical Center at Atlantic City; the New England Regional Office (NERO) in Burlington, MA; and the Air Traffic Service, in particular the tower and IFR room at Burlington, VT and Center personnel assigned to the Boston Center.

SRDS was responsible for planning and coordinating activities with the FAA's Technical Center; it also procured and supplied the Remote Airborne Precision Positioning System (RAPPS) and monitored progress of the CV-580 flight program. The RAPPS provided the CV-580 with a ground reference to evaluate LORAN-C RNAV performance. FAA's NERO was tasked to design non-precision LORAN-C approaches to eight runways at five airports, to review the performance data as it became available, and subsequently to determine the acceptability of applications for Supplemental Type Certificates (STC's) submitted by the State on its request for authorization to operate LORAN-C RNAV in the Cessna 210 and Beech E50 aircraft.

ATC personnel located in Burlington, VT and Boston Center repeatedly assisted the project by accommodating requests for special LORAN-C flights during the 18-month test period.

Vermont's Agency of Transportation was an active participant throughout, supplying test aircraft, conducting engineering surveys of selected locations, coordinating use of facilities throughout the State, supplying flight crews, aircraft and avionics maintenance personnel, and developing new procedures and experimental approaches where it was inappropriate to ask for FAA assistance. Principal technical and operational support to the Agency was provided by Polhemus Associates, Inc. and Air North, Inc., both Vermont companies.

1.4 SUMMARY OF ACTIVITIES

The Vermont LORAN-C Flight Evaluation Program officially commenced in FY 1978; detailed planning was initiated by TSC in June 1978. The Vermont Beech E50 was acquired for this program by the Agency of Transportation in fall 1978 and modified to receive the test equipment during the winter of 1979. NASA completed installation and check out of the data gathering instrumentation in the spring of 1979 at Wallops Island. The data acquisition phase officially began in July 1979 although much of the first five months of flying was devoted to training, debugging of system software, and check out of the ground reference system. Acquisition of LORAN-C ground monitor data began in July 1979 and continued through October 1980.

Between mid-July 1979 and mid-October 1980 the Beech E50 completed 104 flights, totalling 226 hours of LORAN-C RNAV data acquisition in the following areas:

Categories		No. of flights
1.	Pilot Training	4
2.	Ground Reference System Verification	7
3.	Cross Country	4
4.	Project Photo-Documentation	3
5.	Abort-Aircraft Malfunction	1
6.	Aircraft Functional Check Flight	2
7.	Demonstration	21

8.	Procedures Development	16
9.	Data Collection and Documentation	46
	TOTAL	104

During this period four ground-based monitor units (LORAN-C receivers interfaced with tape recorders) acquired extensive data describing various signal parameters. The number of days of accumulated data were:

Site 1,	Burlington Airport (NASA Trailer)	168	days
Site 2,	Burlington " " (Air North Hgr)	193	days
Site 3,	Rutland " "	120	days
Site 4,	Newport " "	131	days

Weather data were acquired for the period of the test from the Burlington Airport Meteorological office of the National Weather Service. This data included plots of temperature, atmospheric pressure, relative humidity and windspeed gathered at six-hour intervals throughout the day.

U.S. Coast Guard (USCG) data describing Northeast chain transmitter availability and records of phase adjustments made by monitor units or the Master at Seneca for the period of the evaluation program were acquired and later compared with the ground and airborne measurements described above. Periods when any transmitter was not available for navigation were included in the reports. A summary of relevant transmitter information appears in Section 2.3.

2. TEST RESULTS

The overall goal of the Vermont test program was to generate a comprehensive data base of technical and operational experience with LORAN-C as an air navigation system. Three specific objectives are discussed: Section 2.1 reviews the primary objective of the test program; Section 2.2 discusses operational and procedural requirements for routine use of LORAN-C in the National Airspace System; Section 2.3 describes LORAN-C signal characteristics as observed within the State of Vermont during the period of the project.

2.1 FLIGHT DATA ACCURACY TEST RESULTS

This section (2.1) provides an overview of the program; among the items included are definitions of errors, descriptions of the airborne test beds, parameters measured, procedures for data processing, methods used in the analysis and a presentation of the results of the analysis.

Two aircrafts were used to estimate the achievable accuracy of LORAN-C when used as an RNAV system: a Twin Beech E50 supplied by the State of Vermont and dedicated full time to this program; a Convair CV-580 supplied by the FAA's Technical Center and used for both enroute and approach accuracy measurements. The first E50 LORAN-C evaluation flight in Vermont was conducted on July 24, 1979; the last evaluation flight was completed on October 15, 1980. The CV-580 aircraft made several trips to Vermont during this time period.

During the first five months 34 flights were flown by the E50 for system integration and checkout, pilot training, ground-truth systems verification and the subsequent modification of the performance of the TDL-711 Micro-Navigator software. In December 1979 the system checkout was completed and no further modifications were made to the LORAN-C navigation system software. The subsequent ten months were used for data collection - seventy flights were flown during this time period.

The standard against which results from the LORAN-C flight tests were compared was derived from the accuracy requirements described in FAA Advisory Circular 90-45A titled "Approval of Area Navigation Systems for use in the U.S. National Airspace System". Several data acquistion requirements evolved from the certification criteria of this document: first, total system error must be calculated; second, the error contributions of the navigation system must be measured; finally, the value of the pilot's contribution to the error budget must be measured.

The advisory circular specifies error boundary (2 sigma) values for each of the three principal flight regimes: enroute, terminal (the instrument departure from the runway to the enroute airspace and, later the arrival or transition leg from the end of the enroute segment to the start of approach at initial approach fix), and approach (the final non-precision approach to runway threshold or the missed approach point at the airport runway).

During the data collection period the Beech E50 completed 169 enroute, 105 terminal or transition segments, and 215 non-precision approaches. Visual observation of the cross track and along track errors was made on every approach segment and, weather permitting, on all transition and enroute segments. Precision measurement of the errors was made on segments from 33 flights which included 66 enroute and 101 terminal segments and 76 non-precision approaches. More than 46,700 measurements of the E50's position were evaluated in quantifying accuracy of the LORAN-C RNAV system.

2.1.1 Error Definition

FAA Advisory Circular 90-45A sets forth RNAV error-budget critera as follows (See Figure 2.1-1):

Along Track Error (ATE) - A position error along the desired track resulting from the error contributions of both the airborne and the ground equipment.

Cross Track Error (CTE) - A position error measured perpendicular from the desired track to the actual position of the aircraft. This error includes the error contributions of the airborne and the ground equipment.

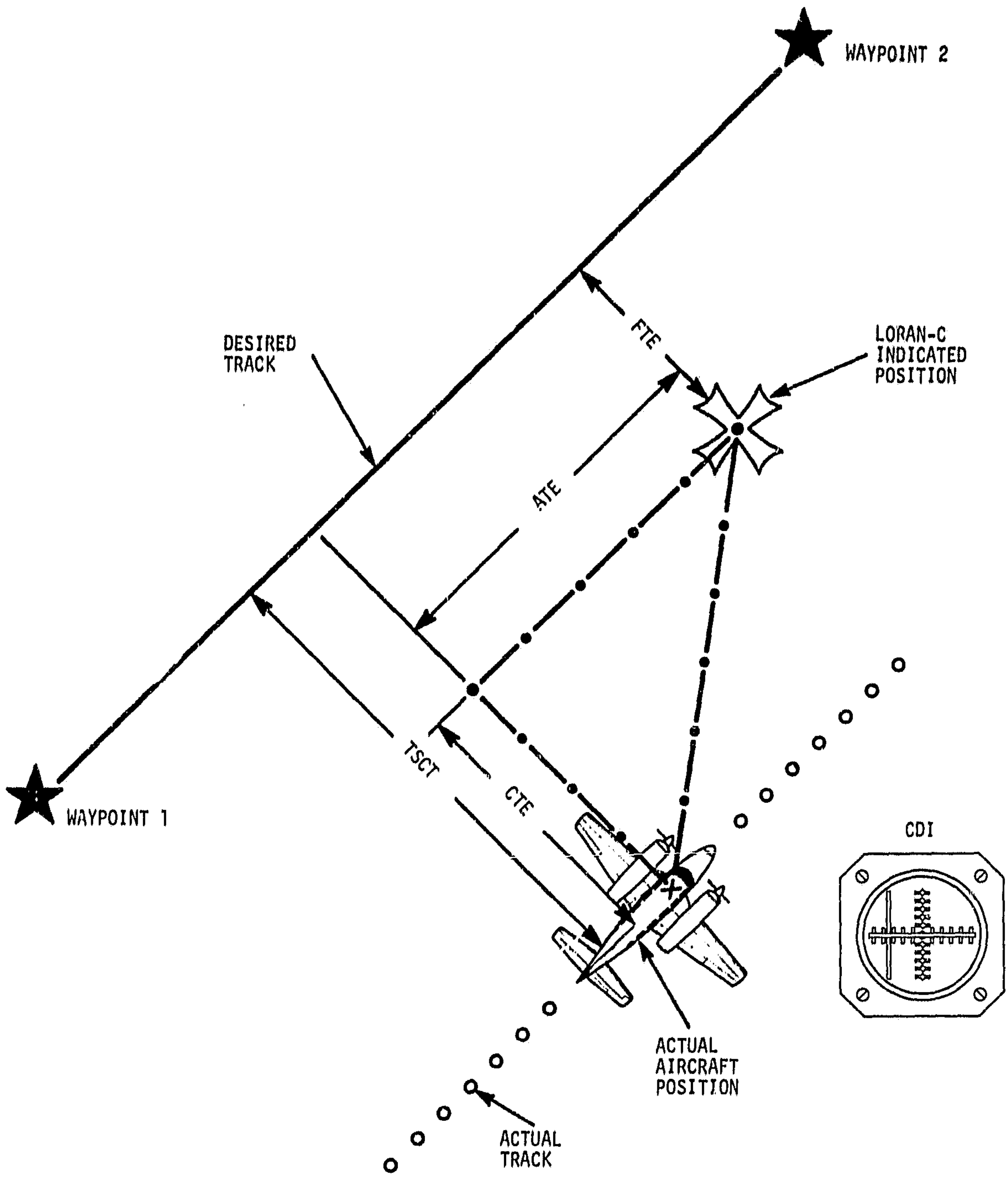
Flight Technical Error (FTE) - This error refers to the accuracy with which the pilot controls the aircraft as measured by his success in nulling deflections of the Course Deviation Indicator (CDI). It does not include blunders which are procedural errors which have gone unnoticed and result in the aircraft exceeding the airspace boundaries. For this test program the boundaries were given in AC 90-45A: ±2.5 nm for enroute segments, ±1.5 nm for terminal segments and ±0.6 nm for non-precision approach segments (all are two sigma, 95 percent, values).

Total System Along Track (TSAT) Error - This error is the ATE and by definition does not include a contribution from FTE.

Total System Cross Track (TSCT) Error - This error is calculated as the root-sum-squares of FTE and CTE.

All the errors were processed as absolute (i.e. magnitude of) deviations from a point on the route centerline. For ATC planning purposes, separation of routes are based on route centerlines and not on achieved mean performance. Increases in the cross track error due to bias from the centerline are thus included in the overall description of achieved performance. When specifying linear accuracy, or when it is necessary to specify requirements in terms of orthogonal axes, the convention adopted in the Federal Radionavigation Plan (FRP) as the 95 percent confidence level will be used.

When two or three dimensional accuracies are used, the 2 drms (distance-root-mean-squared) uncertainty estimate will be used. Drms is the square root of the sum of the squares of the one sigma error components along the major and minor axis of a probability ellipse. Values of drms such as 2 drms are derived by using the corresponding values of sigma. There is a range of values of probability associated with a single value of 2 drms. The variation is not large but it ranges from 95.4% to 98.2% as a function of the ellipticity. The ellipticity is defined as the ratio of $sigma_1$ to $sigma_2$.



TSCT = TOTAL SYSTEM CROSS TRACK ERROR
ATE = AIRBORNE EQUIPMENT ALONG TRACK ERROR
CTE = AIRBORNE EQUIPMENT CROSS TRACK ERROR
FTE = FLIGHT TECHNICAL ERROR

FIGURE 2.1-1. LORAN-C FLIGHT TEST ERROR DEFINITIONS

Three main sources of error contribute to the navigation system error value - the LORAN-C radiated signal, the airborne LORAN-C receiver equipment, and the area navigation equipment. Each of these three main sources are actually composite values including contributions from various factors. For example, the radiated signal errors include propagation errors as well as errors in the transmitted signal.

The navigation system error is the difference between the LORAN-C indicated position of the aircraft and the precision reference system (actual) position of the aircraft at any instant. This navigation system error is then resolved into cross track and along track components.

2.1.2 Test Environment and Equipment

The State of Vermont is situated within the coverage area of the Northeast U.S. LORAN-C Chain (GRI 9960). The primary triad for the test flight program included the master station at Seneca, NY (M), a secondary station at Caribou, ME (W) and another secondary at Nantucket, MA (X). The alternate triad for the test program included the master station at Seneca, NY (M), the secondary transmitter located at Nantucket, MA (X) and a secondary transmitter located at at Carolina Beach, NC (Y). The geographic relationships of the operating area and LORAN-C chain are shown in Figure 2.1-2. The Beech E50 aircraft operated out of Burlington International Airport Vermont which coincidentally lies on the base line between transmiters M and W. The difference in time of arrival of the RF pulses, MW and MX, are referred to as TDA and TDB lines of position (LOPs) throughout this report. The intersection of two or more LOPs defines a position fix and the angle of crossing of the two LOPs establishes the Geometric Dilution of Precision (GDOP).

The LORAN-C RNAV system installed for flight evaluation in the CV580, Beech E50, and Cessna 210 was the TDL-711 Micro-Navigator developed by Teledyne Systems Company. As shown in Figure 2.1-3, this system consists of an integrated control and display unit (CDU), a combined receiver and computer unit (RCU), an antenna with integral coupler, and a course deviation indicator (CDI). In addition, a higher priced military system, the TDL-424, was installed in the CV-580 for comparative evaluation. Detailed characteristics

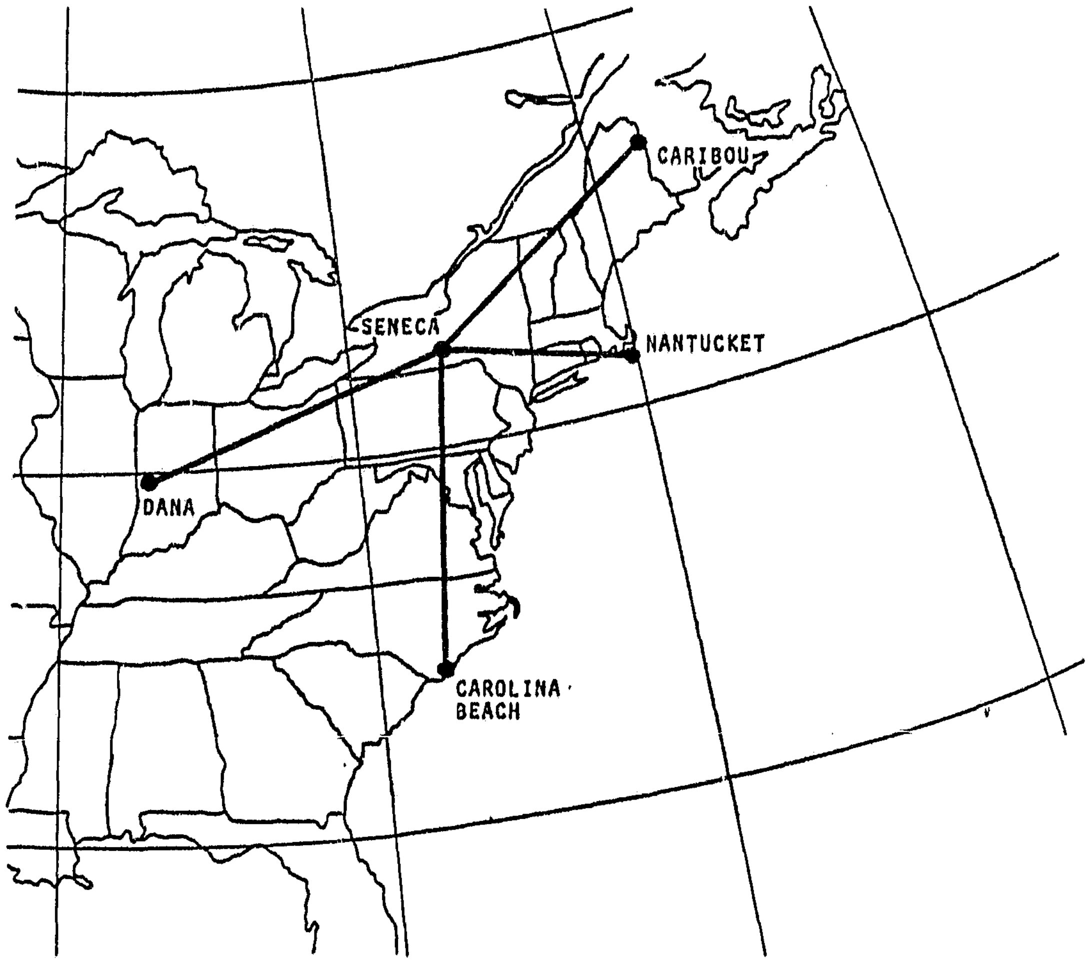


FIGURE 2.1-2. NORTHEAST U.S. LORAN-C CHAIN (GRI 9960)

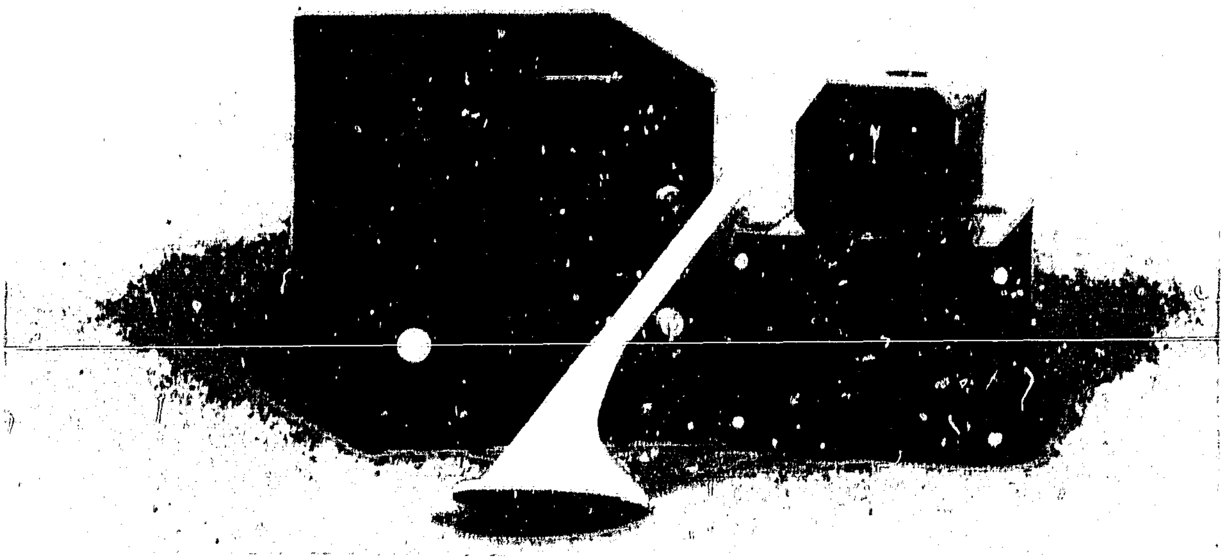


FIGURE 2.1-3. TDL-711 LORAN-C MICRO-NAVIGATOR

of the TDL-711 are provided in Table 2.1-1. The principle difference in the test equipment configuration between the E50 and the CV580 aircraft were in the precision reference system and implementation of command guidance output data. Figure 2.1-4 is a functional diagram of the data acquisition and reference system for the E50.

The airborne instrumentation package in the E50 Beechcraft was designed, fabricated, and installed by the NASA LRC. Flight check of the installation was made at NASA's Wallops test ranges prior to deployment of the E50 to Vermont. Analysis of the measurements taken at Wallops confirmed that the precision reference system provided a ranging accuracy which met the manufacturer's claim of 10 meters (2 drms). In Vermont the transponders of the ranging system (Motorola Mini-Ranger) were installed at existing surveyed radio facilities located on mountain peaks east of Burlington. Their orientation was designed to provide a minimum of two range measurements at four of the Vermont airports incorporated in the program plan as well as much of the enroute airspace in the northern third of the state.

The range-tracking subsystem installed in the CV-580 shown in Figure 2.1-5 used a conventional Distance Measuring Equipment (DME) beacon to obtain range measurements from commissioned or portable ground units. The Remote Airborne Precision Positioning System (RAPPS) was calibrated at the FAA's Technical Center in Atlantic City, NJ. Using the Nike Hercules Radar Tracking system as the standard reference and four commissioned DME ground stations for range measurements, a two sigma range error of 188 meters was calculated without removing range biases. After removing the range bias for each of the DME ground stations, the aircraft position was recomputed to obtain a two sigma range error of 156 meters.

The NASA LRC supplied a fully instrumented trailer, which was based at Burlington, for the dual purposes of recording ground data and of supporting the data acquisition system in the Beechcraft. It also contained a TDL-711 navigator, an Austron LORAN-C receiver, an Omega receiver, a rubidium time standard and various control recording and display equipment (Figure 2.1-6).

TABLE 2.1-1. TDL-711 LORAN-C MICRO-NAVIGATOR CHARACTERISTICS

NAVIGATION SYSTEM	
Mode	Great Circle
Grid Reference (operator selected)	Lat/Long (0.1 min) Time Difference (0.1 usec)
North Reference	True or Magnetic
Waypoints	9 (non-volatile)
Display Resolution	
Distance/Bearing to Waypoint	0.1 nm/1 deg
Estimated Time Enroute/ Ground Speed	0.1 min/1 kt
Cross-Track Distance/ Desired Track	0.01 nm/1 deg
Track-Angle Error/Ground Track	1 deg/1 deg
Offset (input)/Magnetic Variation (input)	0.01 nm/1 deg
Repeatable Accuracy	Better than 0.1 nm
Left-right Steering to CDI	1.25 nm full scale
LORAN-C DATA	
Area of Operation	Two LORAN-C Triads
General	Exceeds RTCA DO-159 Type III Requirements
Acquisition	Automatic
Velocity Envelope (unaided)	0 to 950 knots
Master Independent	Automatic
ENVIRONMENTAL	
Operating Temperature	-55° to 55° C
Altitude (unpressurized)	20,000 feet
Power	18-32 VDC, less than 40 watts
PHYSICAL	
Receiver Computer Unit	7.62H x 7.50W x 12.58D in 11.0 lb
Control Display Unit	4.50 x 5.75W x 6.30D in 4.5 lb
Antenna	16.5H x 2.5W x 10.0D in 0.5 lb

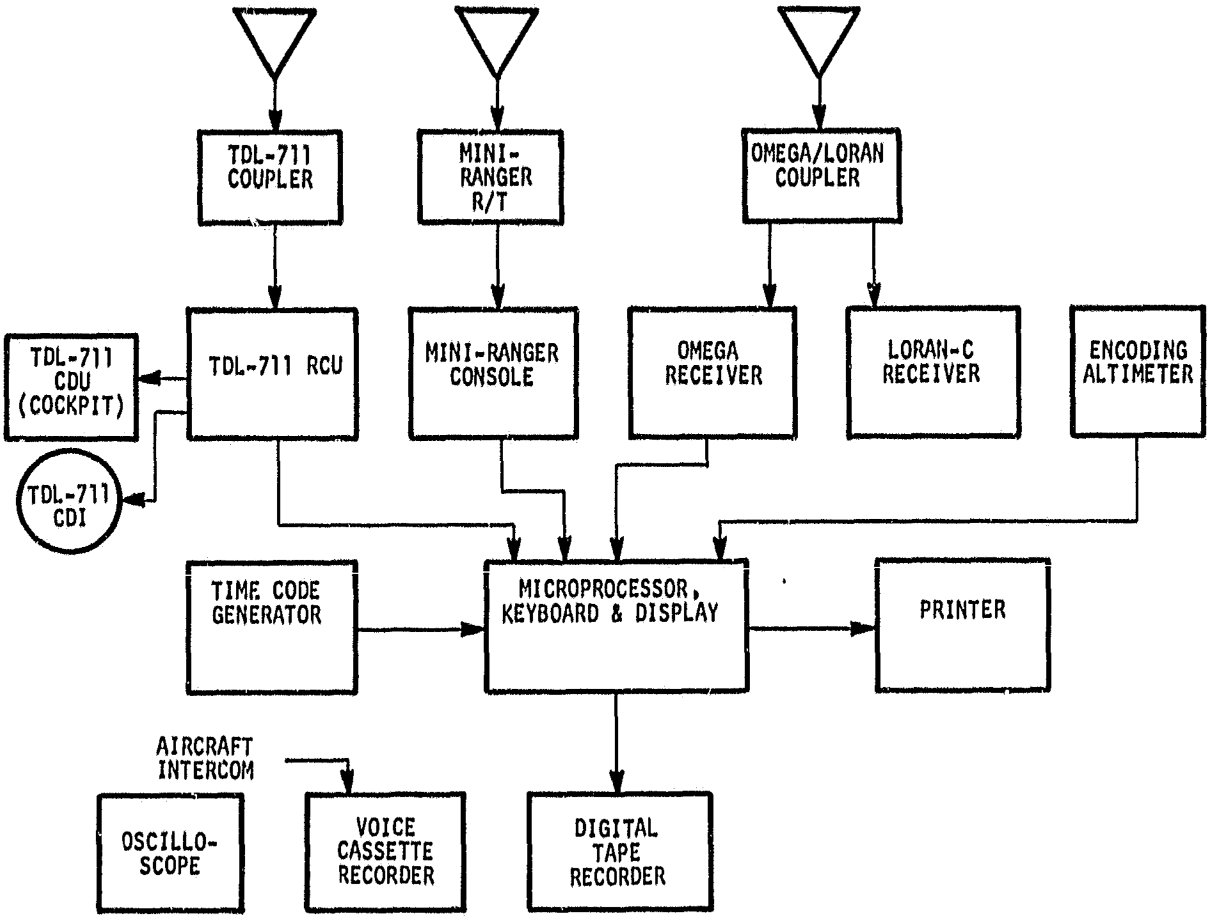


FIGURE 2.1-4. NASA AIRBORNE DATA ACQUISITION AND REFERENCE SYSTEM

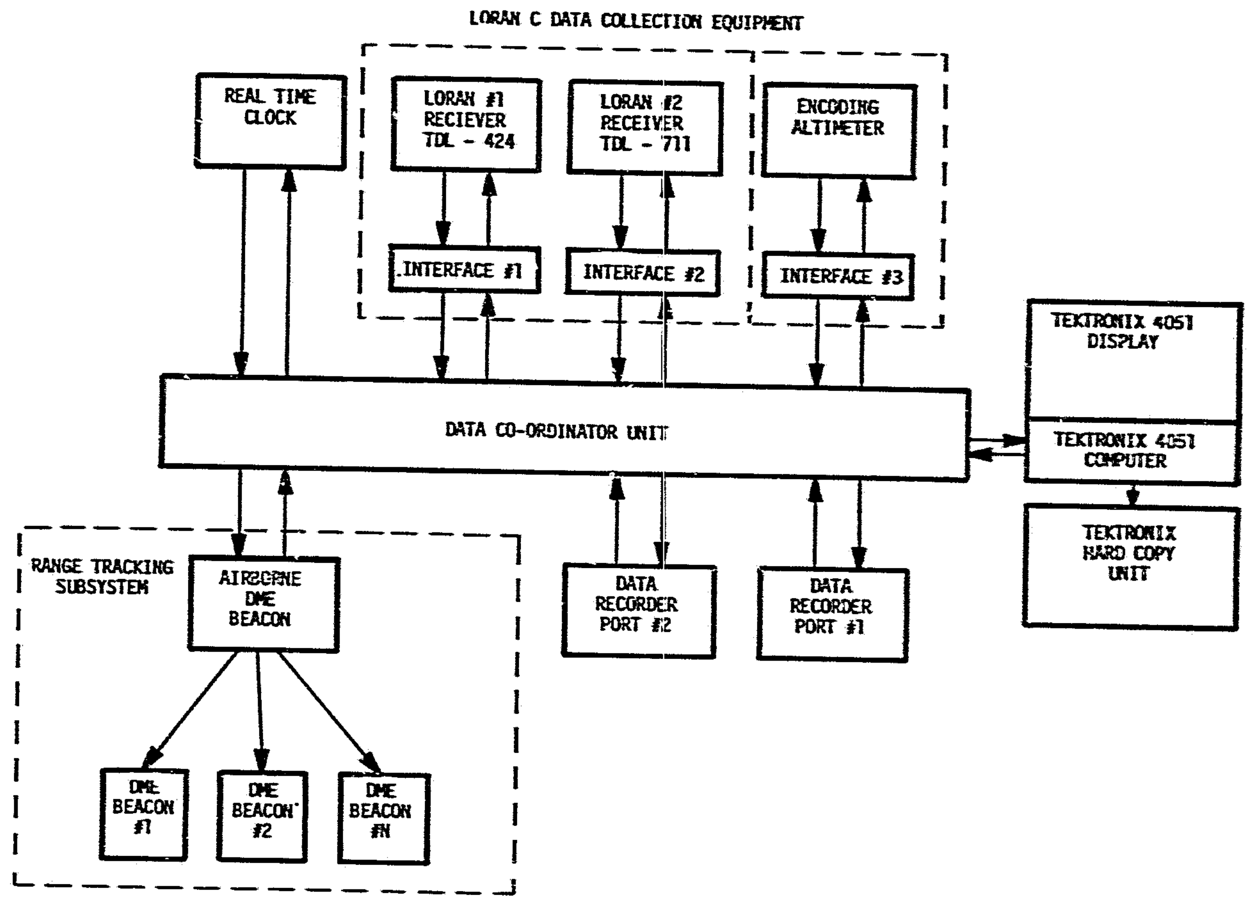


FIGURE 2.1-5. RAPPS DATA ACQUISITION AND REFERENCE SYSTEM

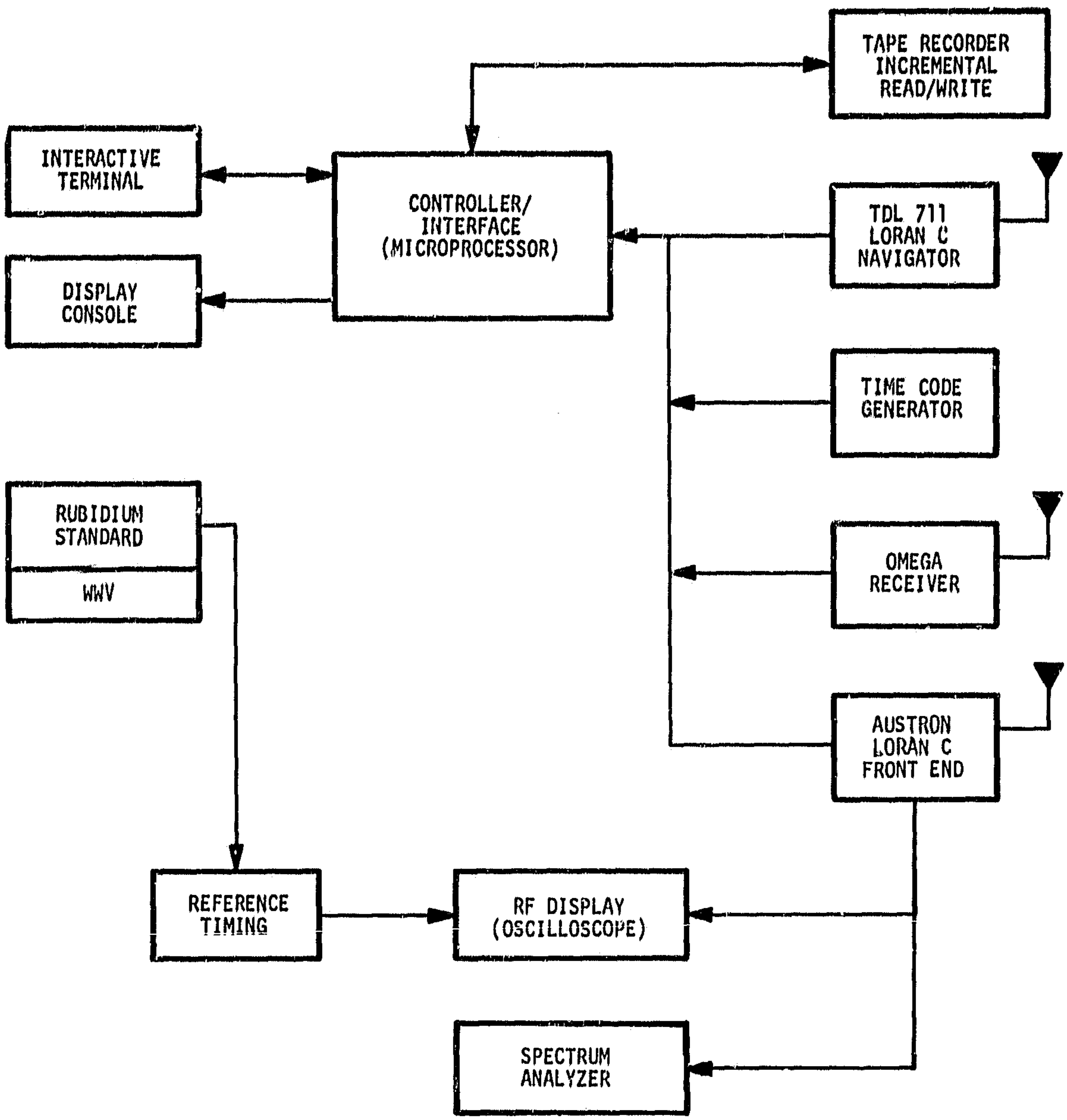


FIGURE 2.1-6. NASA GROUND-BASED DATA ACQUISITION SYSTEM

The State of Vermont conducted a second-order survey of all transponder locations and calibration points at the five test plan airports, using bench marks verified by the National Oceanic and Atmospheric Administration. The survey was referenced to the North American Datum of 1927 and converted by TSC to the World Geodetic System of 1972. This common coordinate reference system was used for all subsequent data processing and analysis.

2.1.3 Data Collection and Processing

The data acquisiton package in the E50 included an incremental recorder triggered once every 0.9 seconds to receive up to 33 discrete variables generated by the TDL-711 (Table 2.1-2), the precision reference system, the Austron time-code generator, and an altitude sensor in the instrumentation package.

The data acquisition located in the trailer was designed to operate in a similar manner, recording similar parameters from the TDL-711, and Greenwich time from a rubidium time standard referenced to a WWV signal.

In addition to the automatically recorded data described above the pilots and flight test engineer were required to complete several forms: Flight Profile Summary, Test Engineers Log, Test Activity Breakdown, Waypoint Log and Flight Log as well as an informal log or set of notes. The flight test engineer also had access to a voice-activated recorder to augment his written notes. A Mission Complete Report was prepared for every flight and submitted with data tapes to NASA and TSC for subsequent review and evaluation. The automated data acquisition was augmented by visual observations by the test engineer of cross and along track errors over each navigaton aid (NAVAID) facility when weather permitted, as well as at the threshold of each runway upon completion of non-precision approach.

Following each flight NASA LRC processed the airborne data recorded in the Beechcraft and prepared an X,Y plot of the flight profile, a scatter plot summarizing error data and an abbreviated (10 variables) data print-out. These data were then forwarded to the TSC and the flight test engineer for review. The X, Y plot provided a ground trace describing the aircraft's route of flight as determined by the LORAN-C system. Whenever Mini-Ranger data was

TABLE 2.1-2. LORAN-C PARAMETERS RECORDED INFLIGHT

EQUIPMENT AND SIGNAL STATUS

- Triad track status
- Signal to noise numbers (M,A,B,C,D)
- Envelope number status
- Current triad in use
- Track flag status

PILOT DISPLAY INFORMATION

- CDU Annunciator lamp status
- CDU display contents
- Current from/to waypoint
- Decimal points and lamps status
- CDI indication (crosstrack error)
- Blink status
- CDI flag status

CONTROL SETTINGS AND MEMORY CONSTANTS

- Function selector switch position
- Hold flag status
- Current offset
- Latitude and longitude of current waypoint
- Magnetic variation
- Area calibration values

OTHER RELEVANT INFORMATION

- Time (hours, minutes, seconds)
- Distance to waypoint
- Ground speed
- Time differences (A,B)
- Current location (L/L)
- Mini-Ranger data

available a second trace was plotted representing ground reference system's indication of the aircraft's position. The origin of the X, Y plots coincided with the coordinates of the calibration site at BTV and the axes were aligned in a True north-south, east-west direction. The profile plot was then annotated from in-flight notes and validated. The enroute, terminal and approach segments were identified and the work sheets returned to NASA for complete processing of the flight measurements resulting in a report of the following statistical information:

1. Coverage plot for the ground reference system
2. Flight X, Y profile plot of the LORAN-C measured geographic position
3. Cumulative probability plots:
    - Along track error by phase of flight
        - Enroute
        - Terminal
        - Approach
    - Flight technical error
        - Enroute
        - Terminal
        - Approach
    - Cross track error
        - Enroute
        - Terminal
        - Approach
    - Total system cross track error (measured)
        - Enroute
        - Terminal
        - Approach
4. Statistical summary chart
5. Scatter plots

A typical flight profile plot and a scatter plot are shown in Figures 2.1-7 and 2.1-8.

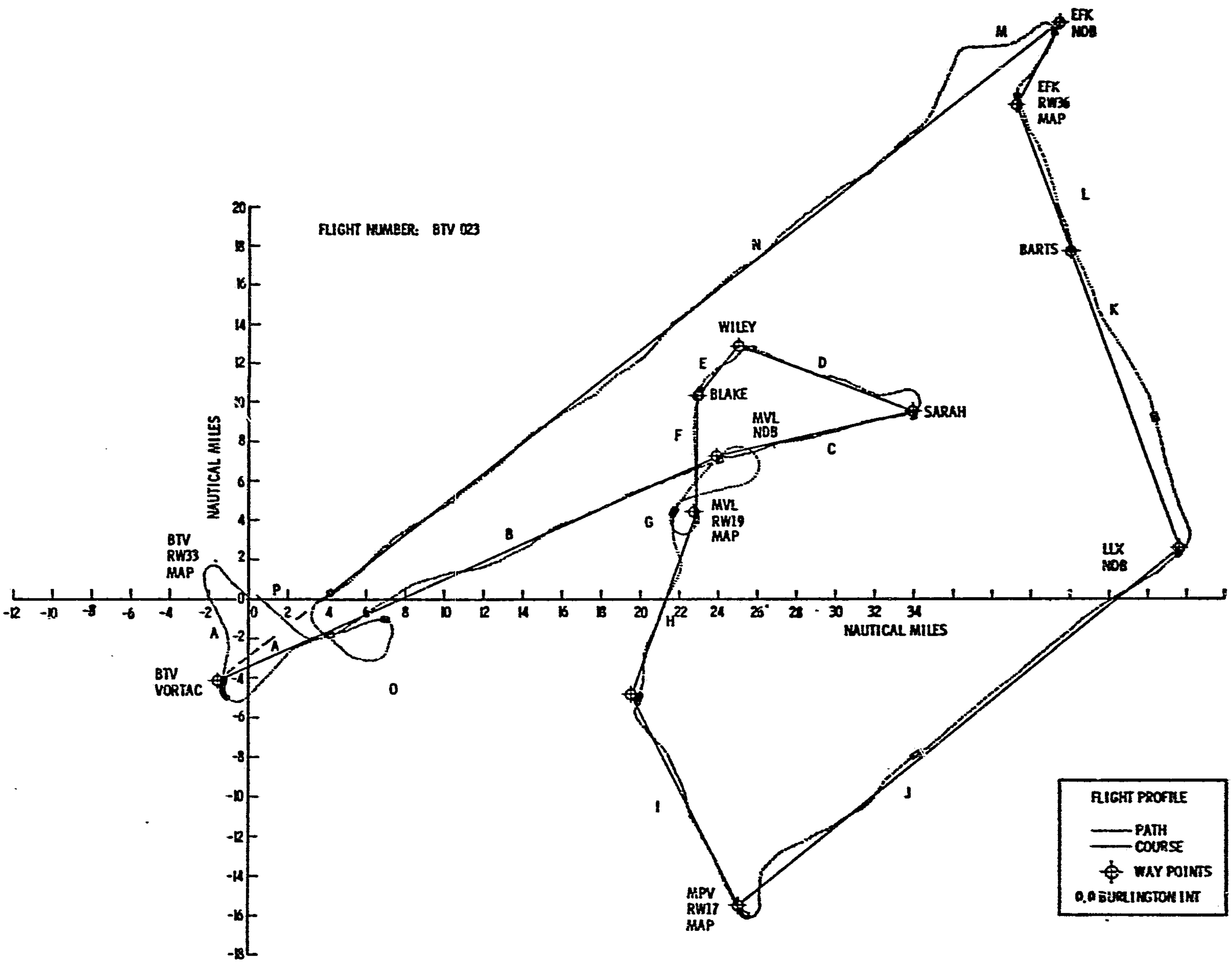


FIGURE 2.1-7. FLIGHT PROFILE FOR FLIGHT BTV 023

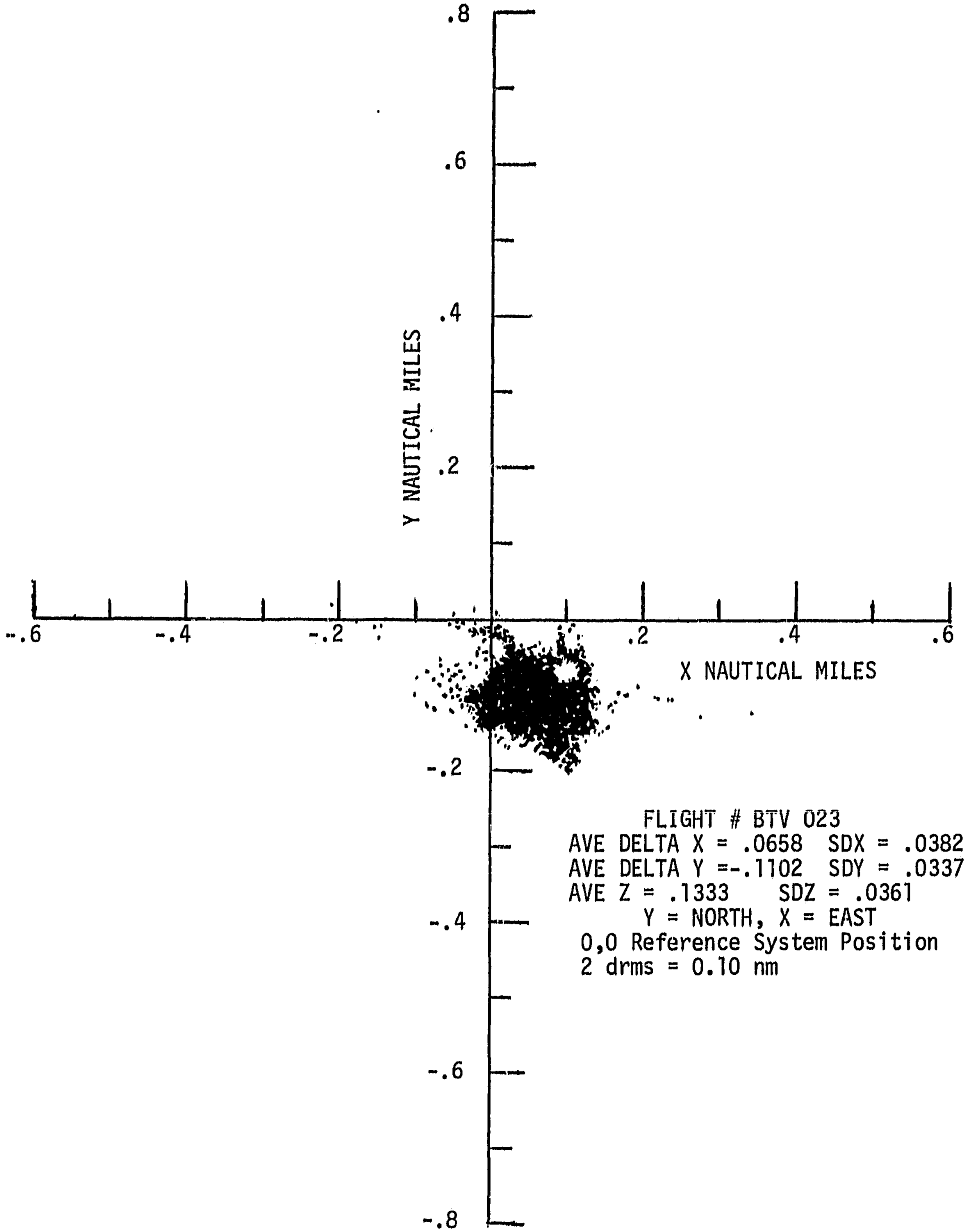


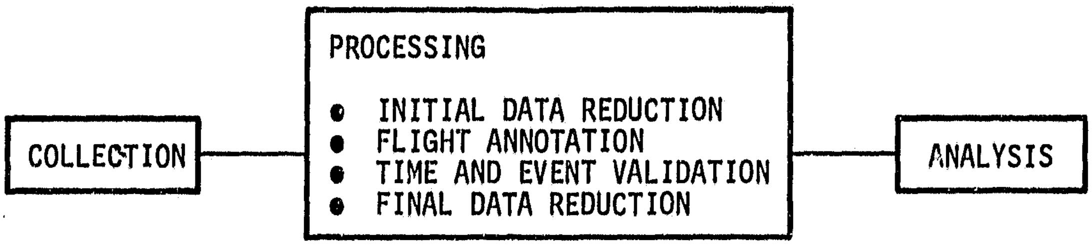
FIGURE 2.1-8. SCATTER PLOT FOR FLIGHT BTV 023

Each point on the scatter plot (1 every 0.9 seconds) represents the position of the aircraft as determined by the airborne LORAN-C navigator; the origin is the position determined by the ground reference system. The vector difference is the error (Z) which was resolved into components along the north (Y) and east (X) axis. On each flight the average X,Y, and Z values and associated standard deviations were calculated as shown here for Flight 023. When the vector is resolved into components along and perpendicular to desired flight path the components become ATE and CTE. The navigation system error, as indicated in Section 2.1.1, is a composite of many errors including variation in the transmitter output, effect of propagation anomalies, survey error, local grid warpage and errors due to the aircraft motion during the recording interval. Some of the individual errors will be quantified in following subsections; however the 2 drms error of Figure 2.1-8 is 0.10 nm, which is significantly smaller than the value specified by AC90-45A, eg 0.45 nm for the approach segment. The scatter plot is representative of the 31 plots analyzed during the test program.

A similiar scatter plot was made from the data collected in the trailer. Each point on the scatter plot (measurements taken once every minute) represents the position of the antenna located on the hanger roof adjacent to the trailer as measured by the LORAN-C navigator; the coordinates of the origin of the plot correspond to position of the antenna as determined by ground survey. The difference between origin and recorded position is the LORAN-C error caused by uncorrected propagation effects, etc. and has similiar composite characteristics as the airborne navigation system error excluding errors caused by aircraft motion during the recording interval. The data preparation system is described in Figure 2.1-9.

2.1.4 Analysis Summary

The data were analyzed in several ways so as to demonstrate the suitability of LORAN-C RNAV for operation in the NAS. The following tasks were accomplished:



ACTIVITY	RESPONSIBLE ORGANIZATION	ACTIVITY OUTPUT
Collection	State of Vermont	Flight Data Tape Mission Complete Report
Processing		
● Initial Data Reduction	Langley Research Center	Scatter Plot Flight Profile
● Flight Annotation	State of Vermont	Segment and Time Selection
● Time and Event Validation	Transportation Systems Center	Segment and Time Validation
● Final Data Reduction	Langley Research Center	Statistical Summary
Analysis	Transportation Systems Center	Interpretation and Aggregation

FIGURE 2.1-9. DATA PREPARATION SYSTEM

1. The 95 percent value of the various error categories was calculated so as to demonstrate compliance with performance criteria contained in AC90-45A.

2. Error data taken from 33 flights were aggregated by flight phase into single sets of numbers.

3. The measured value of TSCT was compared with the calculated value for the aggregated data, to reveal that the difference was not significant.

4. The relative significance of the value of FTE was determined for each of the phases of flight. One flight was analyzed to determine: "To what extent does the pilot's FTE value decrease as he approaches the runway threshold?"

5. The ground and airborne error data were separated into random and bias errors. Calculations were made of the 2 drms value of the random errors and related to their CTE and ATE, components and subsequently compared with relevant criteria in AC90-45A.

6. The bias errors of the flight data were compared with the bias error of ground data to demonstrate that both sets have common seasonal characteristics.

7. The visual estimates of cross track error abeam runway threshold completed for each non-precision approach were analyzed with respect to runway true heading and azimuth of TD LOPs as a cross check against calculated values of grid bias.

8. Error significance tests were completed to disclose the presence, if any, of differences in performance between day and night operations.

9. Comparisons were made of variations in the TD values for the secondary transmitters W and X, as a function of seasonal changes.

10. Significance tests were performed to determine differences in system performance as a function of direction of flight.

11. Extended flights were made to show that the test results were not restricted to Vermont; i.e., the conclusions reached are valid throughout the LORAN-C coverage area.

12. The potential of differential LORAN-C system was evaluated to show a slight improvement in CTE and ATE could be realized from its use.

FTE, CTE, ATE, and TSCT were plotted as cumulative error distributions. The 95 percent error values for this distribution were then determined. Figure 2.1-10 presents a plot of the cumulative error distribution. Each flight (33) which was flown within the precision test range was analyzed by this method.

2.1.5 Results and Conclusions

This section describes the results obtained from evaluation of the flight tests conducted in the Vermont E50 aircraft. The statistical conclusions relate only to those flights or flight segments where the aircraft operated within range of the ground truth system. Measured performance was shown to exceed the minimum requirements specified for area navigation in FAA Advisory Circular 90-45A for all phases of flight. Signal reliability for the 104 flights was determined to be 99.7 percent. The receiver was not affected by any noise sources found at either the medium size or small airports in Vermont or communities in other states into which the aircraft operated. The LORAN-C measurement demonstrated a long term stability (e.g., relative insensitivity to seasonal changes) of .06 nm peak to peak. The LORAN-C RNAV system was found to be satisfactory for non-precision approaches at all test site airports once the runway threshold latitude and longitude coordinates were verified. Accuracy was further improved by inserting locally measured parallel offset values. It was concluded that the LORAN-C transmitter signals and the airborne navigator meet all relevant criteria for RNAV throughout the area of operation.

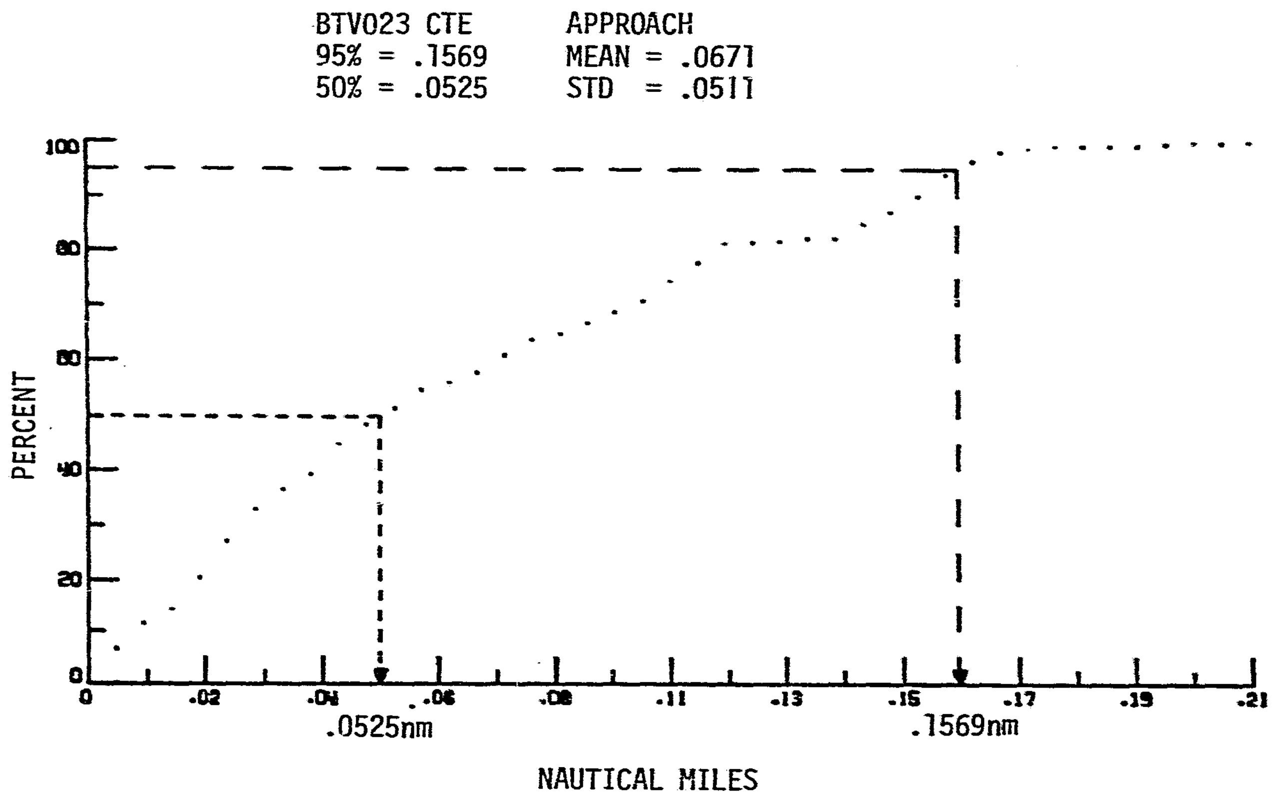


FIGURE 2.1-10. CUMULATIVE DISTRIBUTION OF ERROR FOR FLIGHT BTV-023

2.1.5.1 Enroute, Terminal and Non-Precision Approach Operations - For this evaluation program the enroute segments which connected two airport terminal areas were defined as legs of at least 15 nm and generally were 30-40 nm. Terminal segments include both the departure leg and the transition segment from enroute airspace to the initial approach fix. The approach segment, connects the initial approach fix to the runway threshold on the missed approach way-point.

During the test period from December 5, 1979 to October 15, 1980, 66 enroute segments were completed within the precision test range. A total of 29 flights were analyzed for compliance with the accuracy requirement of AC90-45A. In all error categories, the values of FTE, CTE, TSCT and TSAT were determined to be substantially less than the values stated in the advisory document. Table 2.1-3 lists the aggregate of the 29 flights. The mean TSCT plus two standard deviations about the mean value is 0.73 nm as compared with an AC90-45 performance requirement of 2.5 nm. This value was determined from a population of more than 45,000 measurements. The major contributor to the error was Flight Technical Error, a reflection of the ability to null the CDI; the FTE value is 0.71 nm and is also much smaller than the allowed value of 2.0 nm. Evidence that the pilot could null the CDI is documented in the approach segment analyses. Provision of an auto-pilot might have led to a significant reduction in this component of error. For this project it was judged to be unrealistic to demand performance in the enroute phase similar to that which was sought during approach.

One hundred five (105) terminal segments (25 flights) were flown on the precision test range. These segments were analyzed for compliance with the requirements listed in the advisory document. In all error categories the values of FTE, CTE, TSCT and TSAT were determined to be less than those allowed by AC90-45A for terminal phase operations. Table 2.1-4 lists the aggregate of all the flights. The mean TSCT plus two standard deviations about the mean value was determined to be 0.60 nm. More than 22,000

TABLE 2.1-3. AGGREGATED ERROR DATA FOR ENROUTE SEGMENTS

ENROUTE	TOTAL SYSTEM ERROR							
	TSAT - Along Track		TSCT - Cross Track		FTE - Flight Technical Error		CTE - Equipment Error	
	RQD	MEAS	RQD	CALC[1]	RQD	MEAS	RQD	MEAS
29 Flights 66 Segments	1.5 nm	0.12 nm	2.5 nm	0.73 nm	2.0 nm	0.71 nm	1.5 nm	0.15 nm
Number of Measurements		23,127		45,449		45,449		23,116

1 $TSCT = \sqrt{(FTE)^2 + (CTE)^2}$

TABLE 2.1-4. AGGREGATED ERROR DATA FOR ALL TERMINAL SEGMENTS

TERMINAL	TOTAL SYSTEM ERROR							
	TSAT - Along Track		TSCT - Cross Track		FTE - Flight Technical Error		CTE - Equipment Error	
	RQD	MEAS	RQD	CALC[1]	RQD	MEAS	RQD	MEAS
25 Flights 101 Segments	1.1 nm	0.15 nm	1.5 nm	0.60 nm	1.0 nm	0.58 nm	1.12 nm	0.16 nm
Number of Measurements		12,408		22,539		22,539		12,419

1 $TSCT = \sqrt{(FTE)^2 + (CTE)^2}$

measurements were considered in this determination. The result is less than half as large as the allowed value of 1.5 nm. Again the major contributor to the reported 0.60 nm was an FTE of 0.58 nm. Note that the measured value for equipment error was only 0.16 nm whereas the "allowable" equipment performance value is 1.12 nm.

During the test period 76 approaches were flown on the precision test range, Table 2.1-5. Scheduled approaches were made to 8 runways at four different airports: Burlington International, Barre-Montpelier, Morrisville, and Newport. In addition, an imprompt approach was developed for Franklin Co. Airport. Data from the flights were analyzed for compliance with the requirements in AC90-45A. Table 2.1-5 lists the data from 31 flights. The mean plus two standard deviations value of TSCT was 0.32nm This value was determined from a population of more than 17,000 measurements and is compared with the AC90-45A Advisory Circular value of 0.6 nm. Again, the major contributor to the TSCT error value is a FTE component of 0.28 nm. The allowed value is 0.5 nm. In contrast the measured value for equipment error was 0.15 nm.

Visual estimations of cross track error reported for 272 approaches to thirteen runways at nine airports are summarized in Figure 2.1-11. None of the error estimates for the 272 approaches completed during the 16 months of operation exceeded the AC90-45A performance limit of 0.6 nm. Over half of the approaches were completed with an estimated cross track error between 0 - 150 feet and eighty percent of the approaches were completed with an observed cross track error measured at runway threshold of less than 300 feet.

2.1.5.2 Along Track and Cross Track Error. The possibility for error of position in the airborne navigation system affects air traffic control in its efforts to ensure safe, orderly and efficient movement of aircraft. The performance criteria listed in AC90-45A reflects the ATC's input to the development of a useful national RNAV capability. The ability of the LORAN-C RNAV system to meet the specific enroute, terminal and approach performance criteria of AC90-45A have been satisfactorily demonstrated.

TABLE 2.1-5. AGGREGATED ERROR DATA FOR ALL APPROACH SEGMENTS

APPROACH	TOTAL SYSTEM ERROR							
	TSAT - Along Track		TSCT - Cross Track		FTE - Flight Technical Error		CTE - Equipment Error	
	RQD	MEAS	RQD	CALC[1]	RQD	MEAS	RQD	MEAS
31 Flights 76 Segments	0.3 nm	0.16 nm	0.6 nm	0.32 nm	0.5 nm	0.28 nm	0.33 nm	0.15 nm
Number of Measurements		11,198		17,949		17,949		11,229

1 $TSCT = \sqrt{(FTE)^2 + (CTE)^2}$

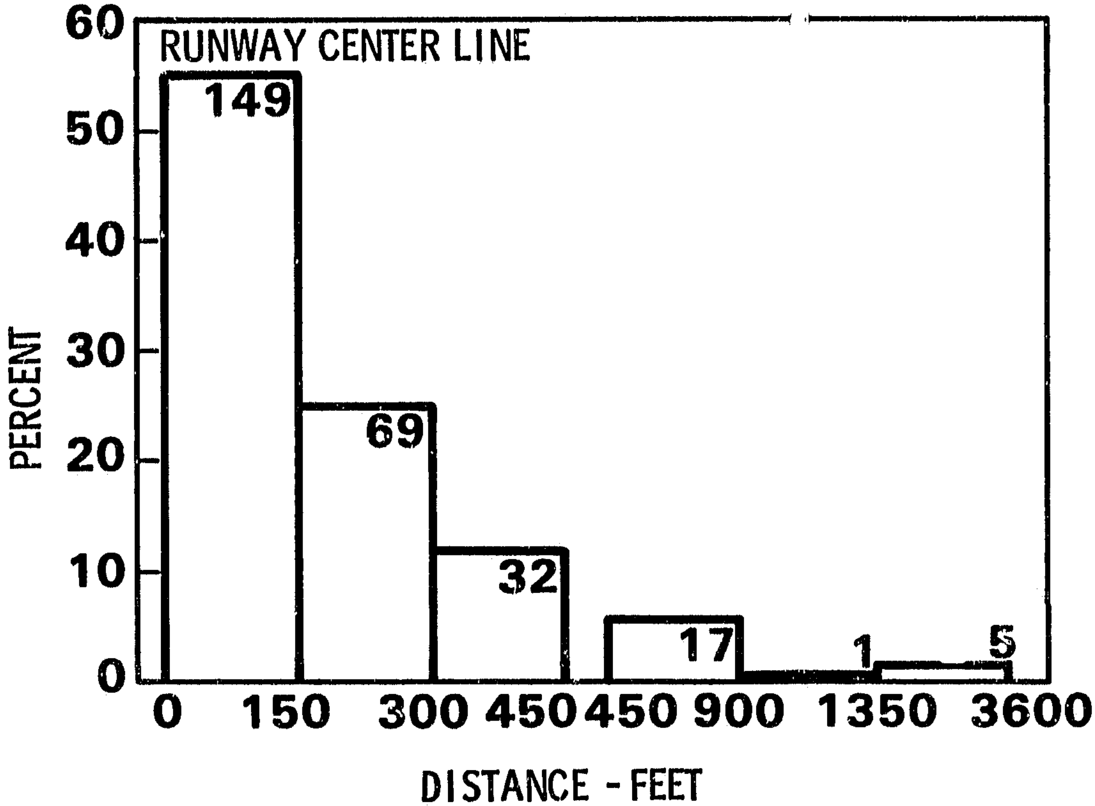


FIGURE 2.1-11. DISTRIBUTION OF CTE DURING APPROACHES (VISUAL OBSERVATIONS)

Tables 2.1-6 and 2.1-7 summarize these results in terms of ATE and CTE (FTE excluded) and compares them with the requirements of the Advisory Circular. The summaries illustrate the fact that the errors are essentially independent of phase and direction of flight; there is no significant difference between the cross track and along track values. This is exactly the result one would expect to observe from evaluation of a large number of measurements taken from randomly oriented routes: a cross track bias on an approach to a particular runway would appear as an along track bias on an approach to a perpendicular runway.

The measured navigation system equipment error (defined in Section 2.1.1) is made up principally of bias error, and random error. The bias error is a result of many factors including grid bias and local warpage. In addition these errors contained components related to aircraft dynamics, the airborne data gathering instrumentation, and small errors in exact knowledge of the geographic location of the transponders. Since these errors were relatively constant it was possible to measure their values by flying a system calibration routine within the reference system grid.

The aircraft was directed to fly a series of north-south, east-west legs approximately 25 nm in length holding constant speed and track. The procedures were repeated on several flights over a period of a month. The airborne data were then processed so that biases in the recording system were identified.

From the analysis it was clear that the recorded LORAN-C position lagged the actual position of the aircraft by approximately .02 nm (122 feet). Table 2.1-8, the source of this error was the length of the interval between data updates (<.9 second) and the averaging process used in presenting the flight data. First the LORAN-C parameters were recorded, then the range measurements from each antenna - top and bottom - were recorded: meanwhile the aircraft was moving along its path at 150 knots.

TABLE 2.1-6. LORAN-C ALONG TRACK ACCURACY

Flight Phase	Measured Mean Error Plus Two STDs (nm)	AC90-45A Two STDs (nm)
Enroute	.13	1.5
Terminal	.15	1.1
Approach	.16	.3

TABLE 2.1-7. LORAN-C CROSS TRACK ACCURACY

Flight Phase	Measured Mean Error Plus Two STDs (nm)	AC90-45A Two STDs (nm)
Enroute	.15	1.5
Terminal	.16	1.12
Approach	.15	.33

TABLE 2.1-8. COMPUTATION OF THE MEAN ERROR IN POSITION CAUSED BY AIRCRAFT MOVEMENT WHILE RECORDING DATA

DIRECTION OF FLIGHT	ERROR CATEGORY	MEAN ERROR (nm)	Δ ERROR[1] (nm)
East	ATE CTE	-.06 -.05	-.02 0
West	ATE CTE	-.02 -.06	+.02 -.01
Combined East and West	ATE CTE	-.04 -.05	0 0
North	ATE CTE	-.08 -.04	-.02 0
South	ATE CTE	-.04 -.04	+.02 0
Combined North and South	ATE CTE	-.06 -.04	0 0

[1]Direction - Combined = ΔError
East ATE - Combined East and West ATE = -.02
West ATE - Combined East and West ATE = +.02
A (-) ΔError is more West than the mean value of the combined directions [(-) More South]

In a few instances transponders were repositioned after the site surveys were completed to improve a units "field of view" resulting in small errors in knowledge of position. The mean error in the knowledge of transponder coordinates was determined to be in the 100 foot range. This error was not caused by errors in the survey, but rather by incorrect estimates of direction and distance in repositioning of the transmitters. On two occasions accumulations of ice coupled with high wind literally tore transponders from their mounts. In both cases the units were reinstalled in more sheltered locations but new range surveys or accurate measurements of the distance moved could not be made because of the snow cover and other environmental conditions. During the data processing activity and the analysis effort no attempt was made to compensate for these small error sources.

The TDL-711 system software is designed to partially compensate for speed of propagation over land paths by assuming a velocity of propagation that is slower than is used for seawater paths. The uncompensated portion of the velocity term causes both TD values used for a fix to be a higher value in microseconds, 0.3 to 0.4 microseconds, than would be the case if the paths were entirely over seawater. The resulting latitude and longitude calculations are therefore more west and south of the true position (by 200 to 300 feet) than they should be. This bias error is the principle source of the errors in position. An estimation of the value of the bias error was made with a linear regression analysis of the data collected in the instrumented trailer. The analysis revealed a south and west mean bias of .03 nm and .02 nm. This bias is much less than the resolution of the displayed latitude and longitude values (.1 nm) in the TDl-711 navigator. The magnitude of the grid bias error appears not to warrent either an adjustment to the assumed propagation velocity value in the navigator or compensation while processing the data. The magnitude of the grid bias error for the secondary triad is discussed in Section 2.1.5.6.

One more error source was evaluated. The temperature along the propagation path affects ground conductivity which in turn has an effect on the propagation velocity. This effect is described in detail in Section 2.3. The peak-to-peak variation was determined to be .06 nm; the period of the

variation was one year. It may be possible to provide a simple first-order grid compensation algorithm in the navigator which is valid for an entire season. However, this error variation is also much less than the displayed resolution in the TDL-711 and does not seem to warrant compensation.

There are additional second order effects on the propagation velocity which would also be considered as bias errors but they have an order magnitude smaller effect than the aforementioned errors. Therefore, investigation of these second-order terms was restricted to a summary taken from a review of appropriate literature, (Reference 1 and 2).

Table 2.1-9 lists 33 of the 104 flights and presents the computed 2 sigma values of CTE and ATE for each phase of operation for each flight, except as noted. The bottom line of the table shows the aggregate value and the corresponding AC90-45A value. Dashes are used to indicate the absence of measured values. All the error values are seen to be within the 2 sigma boundaries given in the circular.

Table 2.1-10 lists those flights where either a single approach was made or all the approaches flown were to the same runway. The 2 drms values and the associated probabilities are to be compared with the 2 drms value of AC90-45A. The first 11 approaches listed are to BTV RW15 and the 2 drms values range from .026 to .031 nm. The second group of approaches are to BTV RW01 and the 2 drms values range from .043 to .173 nm. The AC90-45A allowed 2 drms value is .446 nm with a probability value of 98.2 percent. As a final comparison two flights with approaches to different runways have been included. There does not appear to be any observable bias error in the approaches that would warrant compensation either in the navigation system or in the data analysis.

2.1.5.3 System, Equipment and Flight Technical Error - The total system error has been identified in Section 2.1.1 as a combination of TSCT and TSAT errors. The TSAT is synonymous with the ATE since FTE does not affect this component; it is discussed more fully in Section 2.1.5.2. The TSCT error, which includes FTE may be calculated by following the formulas in AC90-45A; it may be measured during flight. As shown in Figure 2.1-1, TSCT error is defined as

TABLE 2.1-9. COMPARISON OF CTE AND ATE FOR ALL PHASES OF FLIGHT

FLIGHT	APPROACH		TERMINAL		ENROUTE	
	CTE	ATE	CTE	ATE	CTE	ATE
339-1	.07	.09	-	-	.08	.08
340-1	.08	.04	.07	.13	.08	.04
340-2	.30	.12	-	-	.16	.08
346-1	.20	.14	.14	.17	.14	.11
347-1	.20	.10	.11	.12	.10	.11
347-2	.26	.12	.11	.11	.10	.10
354-1	.19	.16	.15	.11	.11	.18
362-1	.09	.11	.13	.10	.09	.09
021-2	.05	.12	.10	.15	.13	.07
023	.16	.13	.15	.15	.15	.04
024	.13	.17	.16	.17	.39	.28
025	.17	.19	.21	.06	.17	.15
045	.11	.14	.10	.15	.12	.10
080-2	-	-	-	-	-	-
081	.09	.12	.13	.12	-	-
109-1	.07	.09	-	-	.12	.13
109-2	.09	.12	.06	.03	.10	.06
113	.13	.28	.13	.13	.15	.04
116	.09	.07	-	-	.09	.02
127	.12	.26	.16	.14	-	-
129	-	-	-	-	.08	.10
134	.08	.03	-	-	.12	.12
135	.13	.23	.10	.06	.07	.12
136	.08	.03	.07	.07	.09	.06
141	.12	.14	.12	.06	.08	.11
163	.06	.08	.07	.06	.08	.08
165	.10	.28	.04	.10	.16	.26
169	.08	.03	-	-	.14	.11
176	.14	.22	.04	.09	.05	.18
182-1	-	-	-	-	.03	.09
182-5	.07	.03	-	-	-	-
189-1	.15	.18	.08	.37	-	-
189-2	.11	.21	-	-	.54	.43
AGGREGATE*	.15	.16	.16	.15	.15	.16
AC90-45A	.33	.30	1.12	1.1	1.50	1.50

*Mean Error plus two standard deviations.

TABLE 2.1-10. COMPARISON OF THE 2 DRMS VALUES FOR THE APPROACH PHASE OF FLIGHT

	FLIGHT #	APPROACH #	2DRMS (nm)	PROBABILITY (%)
RW15	340-1	1	.032	97.7
	134	1	.027	98.0
	136	7	.026	98.1
	169	1	.028	98.1
	182-5	1	.031	97.4
RW01	109-1	1	.043	96.4
	165	1	.173	97.4
	176	2	.136	97.2
	189-1	1	.112	98.1
	189-2	1	.118	96.7
RW33	127	1	.175	96.0
	135	1	.158	96.2
	141	1	.103	96.8
RW17	340-2	1	.144	95.7
MISC. RW's	339	6	.059	96.6
	116	3	.074	97.9
AC90-45A			.446	98.2

the measured distance, perpendicular from the desired course, to the actual position of the aircraft. Table 2.1-11 compares the calculated and measured values of TSCT error by flight phase for those flight segments which were flown within the reference system. The measured values of TSCT error for all three flight phases are seen to fall within the performance criteria of AC90-45A. It is noteworthy that performance for <u>enroute</u> operations came within 12 percent of meeting the AC90-45A criteria for <u>approach</u>. It will be shown that the major contribution to the TSCT error budget is chargeable to flight technical (piloting) error.

Equipment error is defined in Section 2.1.1 as the navigation system error. Included in this component of the error budget are contributions from the transmitter, propagation medium, airborne receiver and the area navigation equipment. The error vector between actual aircraft position (as measured by the ground-truth system) and the indicated position of the LORAN-C navigator is defined as the navigation system or equipment error. When this vector is resolved into its along track and cross track components they are identified as ATE and CTE. If the vector is resolved into its north and east components it is referred to as northing and easting error. In this report the following convention is adopted: the errors are identified as ATE and CTE when related to track, and X and Y when referenced to east and north. Table 2.1-12 lists the X and Y errors for each flight completed in the precision test range. Table 2.1-13 lists the mean X and Y errors for the ground station. The mean error is a composite of random errors and bias errors. With a joint analysis of the ground data and airborne data one can separate the bias errors from the random errors.

The use of a ground monitor to provide a correction for bias error in airborne equipment is referred to as a differential correction. Flight BTV 362 of December 28, 1979 was processed as if it had been a differentially corrected flight. The scatter plot illustrated in Figure 2.1-12 shows the "before correction" situation. The bias errors were subsequently calculated from the ground data then the flight tape was reprocessed and the calculated bias error corrections were applied algebraically to the individual TDL-711 determined positions. The differentially corrected results are shown in the

TABLE 2.1-11. COMPARISON OF THE CALCULATED VALUE OF TSCT WITH THE MEASURED VALUE

REGIME	CALCULATED TSCT (C) (nm)	MEASURED TSCT (M) (nm)	Δ C-M (nm)
Approach 76 Segments 31 Flights	.320	.294	.026
Terminal 101 Segments 25 Flights	.601	.564	.037
Enroute 66 Segments 29 Flights	.726	.681	.045
AC90-45A Calculated TSCT	APPROACH (nm)	TERMINAL (nm)	ENROUTE (nm)
	.60	1.5	2.5
Aggregate Calculated TSCT	.32	.60	.73

TABLE 2.1-12. INFLIGHT NAVIGATION SYSTEM ERROR

CALENDAR DATE	DAY	MEAN X (nm)	MEAN Y (nm)	MEAN Z (nm)	NUMBER OF SAMPLES
5 DEC 79	105	-.0388	-.0456	.0649	1984
6 DEC 79	106	-.0090	-.0674	.1142	1207
6 DEC 79	106	.0127	-.1037	.1366	1384
12 DEC 79	112	-.0536	-.0939	.1215	4006
13 DEC 79	113	-.0166	-.0629	.0891	2706
13 DEC 79	113	-.0067	-.0635	.0877	4515
20 DEC 79	120	.0273	-.0956	.1124	2114
28 DEC 79	128	.0177	-.0850	.0937	2198
21 JAN 80	152	.0589	-.0920	.1142	2292
23 JAN 80	154	.0658	-.1102	.1333	2665
24 JAN 80	155	.0740	-.1304	.1567	1235
25 JAN 80	156	.0760	-.1279	.1559	2175
14 FEB 80	176	.0446	-.0811	.1014	2717
21 MAR 80	212	.0397	-.1079	.1192	464
18 APR 80	240	-.0401	-.0800	.1080	632
18 APR 80	240	-.0418	-.0592	.0837	828
22 APR 80	244	-.0544	-.0645	.1060	978
25 APR 80	247	-.0355	-.0633	.0806	397
6 MAY 80	258	-.0594	-.0656	.1253	296
8 MAY 80	260	-.0458	-.0521	.0748	47
13 MAY 80	265	-.0381	-.0513	.0752	2216
14 MAY 80	266	-.0510	-.0526	.0903	297
15 MAY 80	267	-.0301	-.0569	.0695	3250
20 MAY 80	272	-.0442	-.0580	.0776	1430
20 MAY 80	272	-.0441	-.0788	.0932	
11 JUN 80	294	-.0271	-.0512	.0689	2007
13 JUN 80	296	-.0502	-.0696	.1007	568
17 JUN 80	300	-.0379	-.0691	.0886	261
20 JUN 80	307	-.0482	-.0567	.0829	1243
30 JUN 80	313	-.0411	-.0376	.0592	62
30 JUN 80	313	-.0247	-.0550	.0654	199
7 JUL 80	320	-.0485	-.0540	.1279	317
7 JUL 80	320	-.0180	-.0589	.0609	201
28 AUG 80	372	.0056	-.0409	.0657	

TABLE 2.1-13. GROUND-BASED NAVIGATION SYSTEM ERROR

MEDIAN DATE	DAY	MEAN X (nm)	MEAN Y (nm)	MEAN Z (nm)	NUMBER OF SAMPLES
23 AUG 79	1	-.0479	-.0294	.0507	559
23 AUG 79	1	-.0491	-.0267	.0565	520
28 AUG 79	6	-.0531	-.0250	.0588	401
31 AUG 79	9	-.0434	-.0353	.0635	848
21 OCT 79	60	-.0432	-.0284	.0518	435
23 OCT 79	62	-.0351	-.0309	.0470	1744
8 NOV 79	78	-.0312	-.0424	.0528	1595
9 NOV 79	79	-.0318	-.0429	.0535	737
19 NOV 79	89	-.0279	-.0313	.0480	806
3 DEC 79	103	-.0258	-.0406	.0487	1464
5 DEC 79	105	-.0219	-.0227	.0322	1000
10 DEC 79	110	-.0280	-.0338	.0440	1000
14 DEC 79	114	-.0104	-.0246	.0272	78
22 DEC 79	122	.0076	-.0416	.0436	1620
29 DEC 79	129	-.0154	-.0177	.0197	922
14 JAN 80	145	-.0065	-.0335	.0355	649
23 JAN 80	154	.0116	-.0458	.0479	653
28 JAN 80	159	.0130	-.0503	.0521	925
5 FEB 80	167	.0127	-.0479	.0505	663
20 FEB 70	182	-.0114	-.0304	.0350	1621
3 MAR 80	194	-.0052	-.0308	.0370	854
29 MAR 80	220	-.0285	-.0351	.0459	1648
21 APR 80	243	-.0382	-.0335	.0518	1000
10 MAY 80	262	-.0418	-.0294	.0520	582
6 JUN 80	289	-.0438	-.0385	.0605	413
8 JUN 80	291	-.0449	-.0328	.0560	188
7 JUL 80	320	-.0432	-.0312	.0539	863
24 JUL 80	337	-.0433	-.0325	.0565	784
1 AUG 80	345	-.0426	-.0305	.0527	159
14 AUG 80	358	-.0419	-.0349	.0549	1262
3 SEP 80	378	-.0356	-.0334	.0496	1591
8 OCT 80	413	-.0304	-.0374	.0490	1229

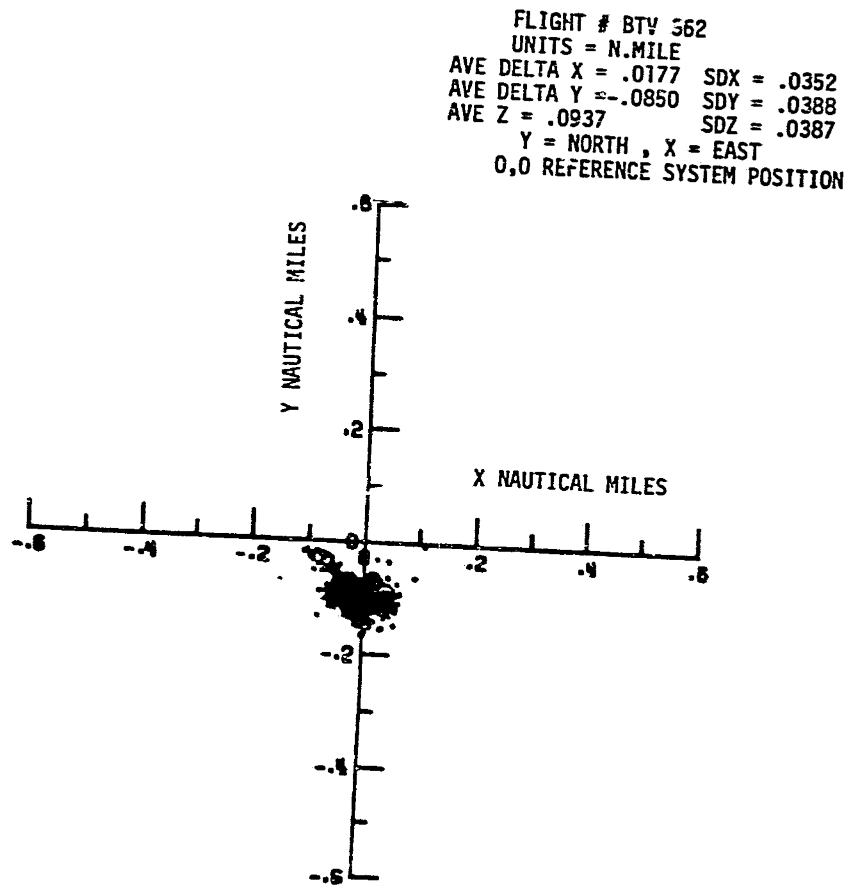


FIGURE 2.1-12. SCATTER PLOT FOR FLIGHT BTV-362

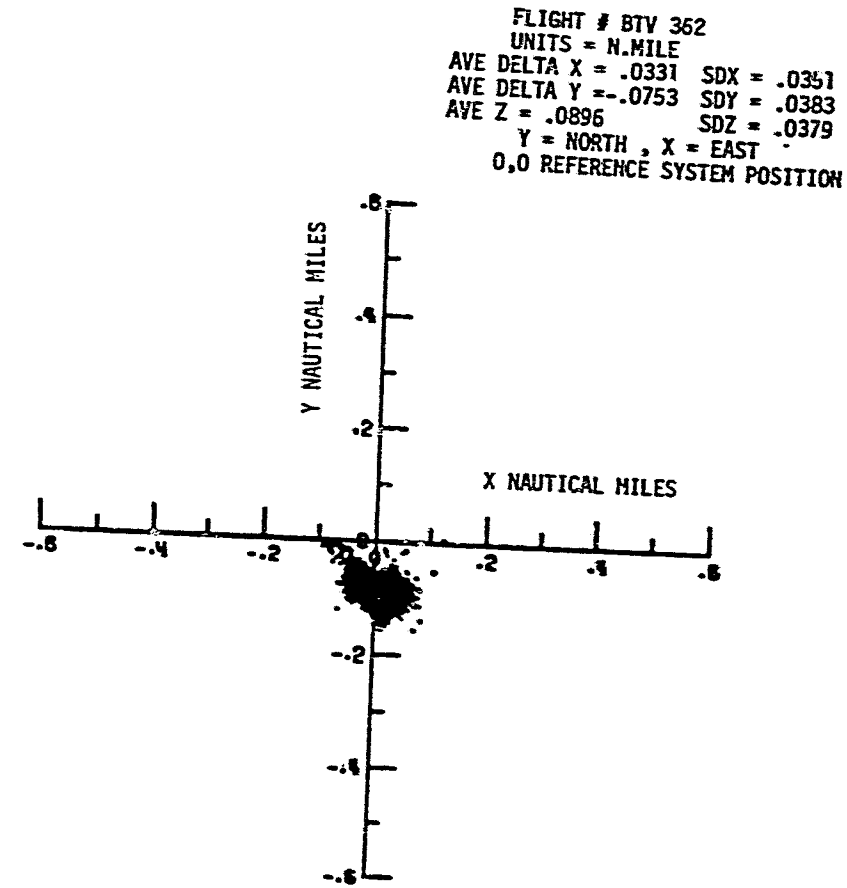


FIGURE 2.1-13. SCATTER PLOT WITH DIFFERENTIAL CORRECTION FOR FLIGHT BTV-362

scatter plot, Figure 2.1-13. The remaining bias error is caused by the bias in the positions of the reference system (see Section 2.1.5.2). The mean navigation error is reduced by .004 nm. The bias error is due primarily to conductivity considerations which were shown to be small for the primary triad. Examination of Figures 2.3-11 and 2.3-12 in Section 2.3 describes the temporal variation in TDA and TDB. It will be observed that the mean error in TDA and TDB were at their minimum values at the time of this flight, in December 79. However, even at the time of peak error (mid-June) the figures show that the bias correction for the primary triad would by less than .06 nm.

The term flight technical error is used to describe the performance of pilot (or autopilot) in keeping indicated cross track distance at or near zero as evidenced by explicit readout of the cross track distance readout on the CDU and out-of-null displacement of the command steering needle on the CDI. The CDI is a command display which shows the pilot the direction to steer to return to track. A scale factor switch was added to give the pilot the option of selecting 1/4, 1/8, or 1/16 nm per dot. This offered sufficient sensitivity to assist the pilot in making an approach with the inherent accuracy of the navigation system. The Advisory Circular specifies allowable values of FTE to be combined with measured CTE when determining TSCT error. In all flights analyzed for the project, the measured FTE was less than the allowed value. FTE performance was analyzed in detail on flight BTV 136 because seven consecutive approaches were made to the same runway BTV RW15 under essentially identical conditions. The initial approach waypoint is located 9.6 nm from runway threshold. The error statistics were determined for the seven approaches for the full 9.6 nm approach and then re-determined for the final 4 nm. A significance test was performed to determine whether the pilot's noticeably improved performance during the final four nm of the approach could have happened "by chance".

The results of the analysis indicated that only once in one hundred trials would one attribute the improved performance to chance, the remaining 99 occurances could be attributable to the stimulus of the approaching threshold. The X, Y plots of the flight profiles for the seven approaches is shown in Figure 2.1-14; the supporting data is presented in Table 2.1-14. It will be noted that the CTE and ATE 2 sigma error values are essentially constant for

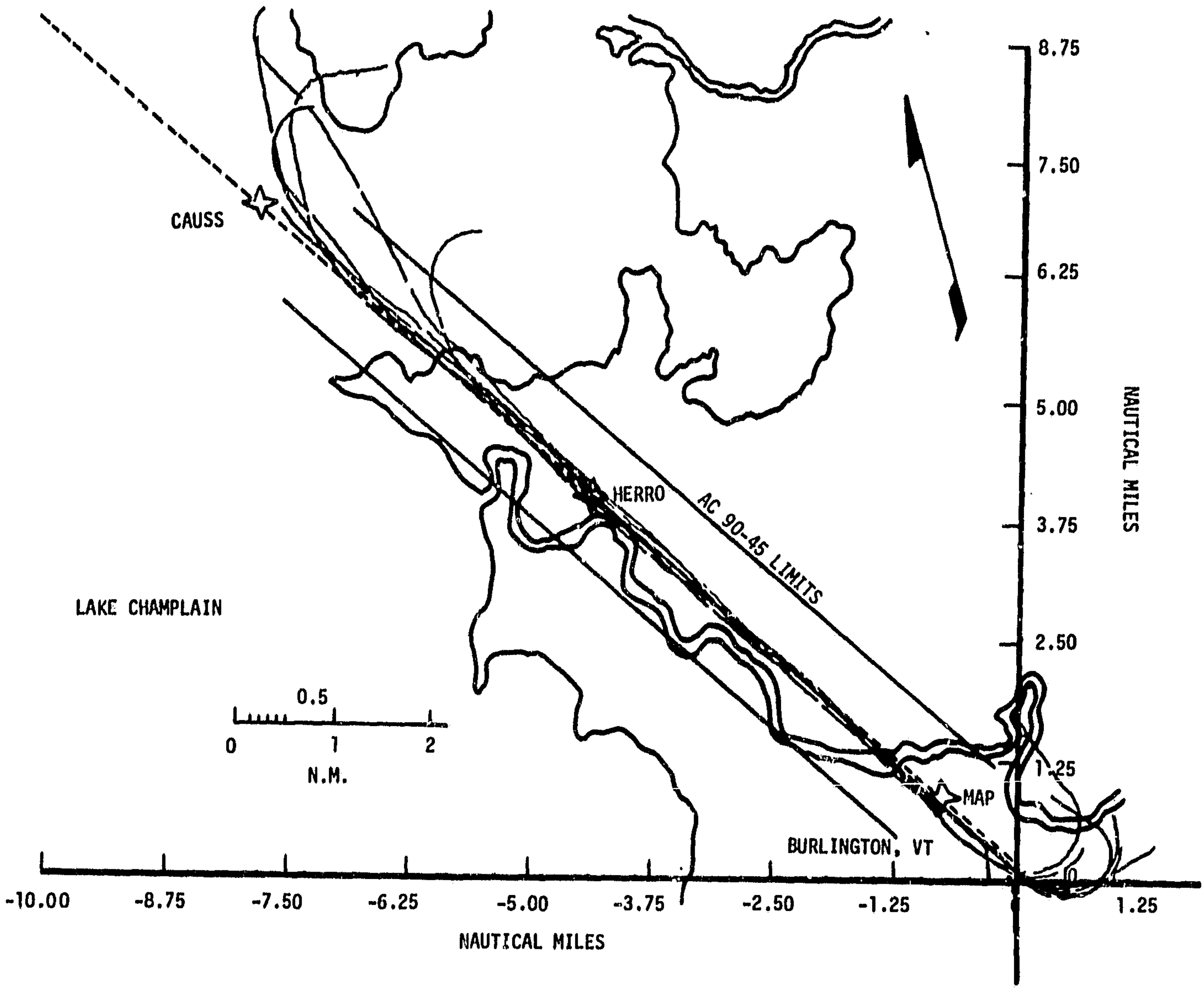


FIGURE 2.1-14. LORAN-C APPROACH SEGMENTS (7) TO RUNWAY 15 AT BURLINGTON VT ON MAY 5, 1980

TABLE 2.1-14. COMPARISON OF FTE AT 8 MILES AND AT 4 MILES FROM THRESHOLD

	TOTAL SYSTEM ERROR				FTE - Flight Technical error		CTE - Equipment Error	
FLIGHT BTV-136	TSAT - Along Track		TSCT - Cross Track					
	RQD	MEAS	RQD	CALC[1]	RQD	MEAS	RQD	MEAS
FULL APPROACH 8 MILES	0.3 nm	0.03 nm	0.6 nm	0.20 nm	0.5 nm	0.19 nm	0.33 nm	0.08 nm
PARTIAL APPROACH 4 MILES	0.3 nm	0.02 nm	0.6 nm	0.13 nm	0.5 nm	0.10 nm	0.33 nm	0.08 nm

1 $TSCT = \sqrt{(FTE)^2 + (CTE)^2}$

both the 9.6 nm approach and the last 4 nm of approaches whereas FTE is halved during the last 4 nm. Figure 2.1-15 presents a plot of mean FTE plus two standard deviations about the mean for each one-half mile increment along the approach. The approach corridor is bracketed at plus or minus 0.6 nm with the AC90-95A boundaries. The plot clearly indicates that as the pilot increasingly directs his attention to the CDI, the FTE approaches zero.

2.1.5.4 Diurnal Effects - Diurnal TD variations are temporal variations which occur on a daily basis. These shifts might be caused by a variation of solar activity or changes in humidity over the period of a day. In Section 2.3 are plotted the TDA and TDB diurnal variations. From Figures 2.3-15 and 2.3-16 it is evident that during the first twelve hours (GMT) the signals are very stable; most of the diurnal variation is seen to occur during the last twelve hours of the day (coincident with daytime temperature changes). To verify that the diurnal effect was not significant as regards performance of the LORAN-C navigator two comparisons were made: The first compared the measured CTE and ATE experienced on two approaches completed 4 hours apart on the same day during the diurnally active period and to the same runway (BTV RW01); the second comparison was of the CTE and ATE values obtained from analysis of five approaches to runway 15 at Burlington on different days and during two time periods. The results obtained from the first comparison appear in Table 2.1-15: the 2 sigma error values of CTE and ATE for flights 189-1 and 189-2. The approaches were to RW01 at BTV. The two time periods, 1500 and 1900 fall within the period of the most active TD variations. The 2 drms values were calculated; no significant difference was established. In Table 2.1-15 were presented the results obtained from the analysis of the five flights to the same runway, RW15 at BTV. The first group of three approaches were completed between 1400 to 1800 hours (GMT) and the second group were completed during the period 2100 to 0200 hours. A comparison of the 2 sigma CTE and ATE as well as the 2 drms show no significant difference.

2.1.5.5 Seasonal Effects - There is a potential for change in ground conductivity to produce significant variations in TD values. The variation of TD value with season is described in Section 2.3: the effect was determined not to be significant. Table 2.1-16 is a comparison of five flights. All flights made approaches to BTV RW15. The direction of CTE is normal to the

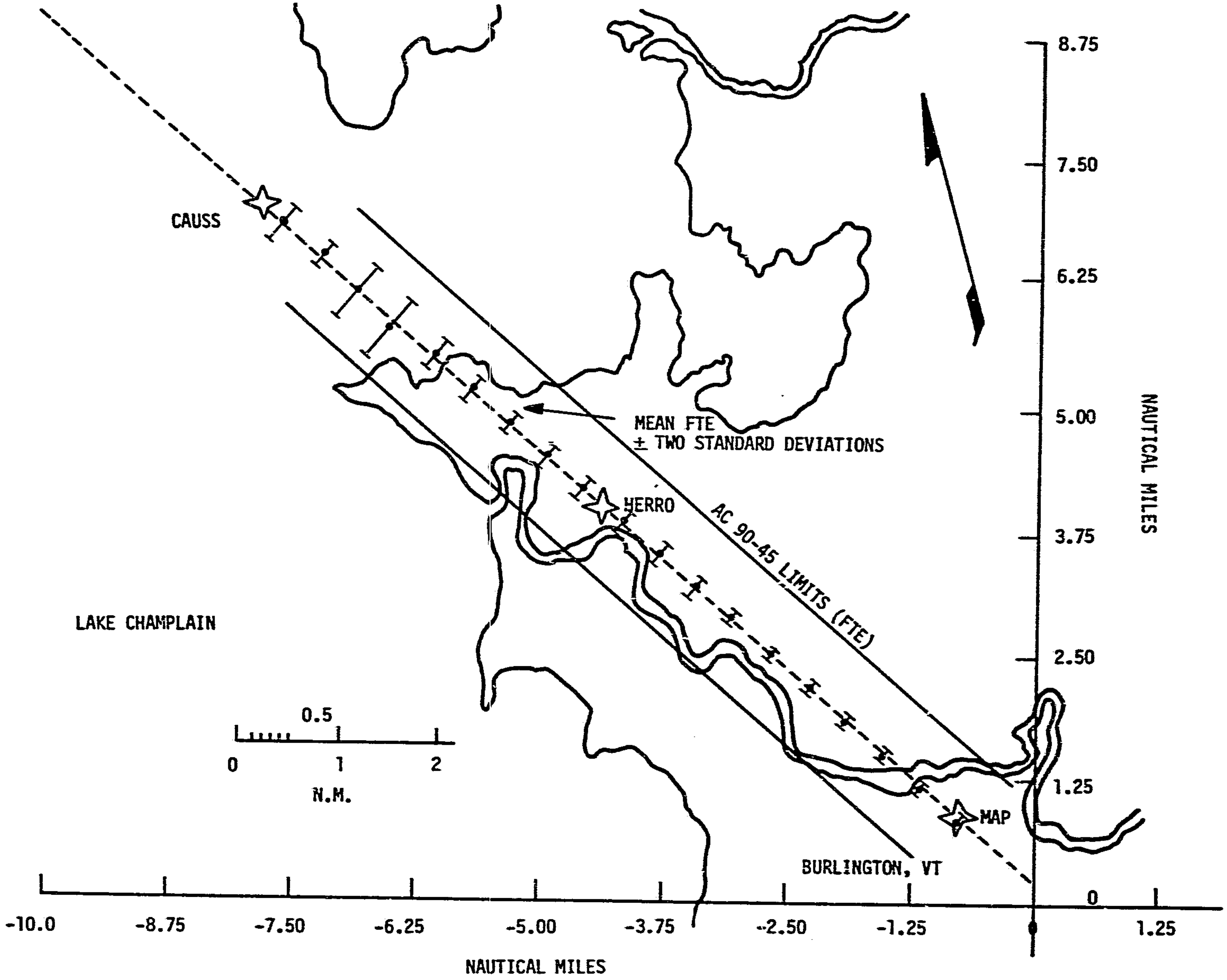


FIGURE 2.1-15. IMPROVEMENT IN FTE ALONG THE APPROACH

TABLE 2.1-15. DIURNAL EFFECT ON TWO FLIGHTS ON THE SAME DAY TO THE SAME RUNWAY

BURLINGTON RUNWAY 01	CTE (nm)	ATE (nm)	2drms (nm)	PROBABILITY PERCENT
Flight BTV 189-1 (1500 to 1700 hours) GMT	.15	.18	.23	98.0
Flight BTV 189-2 (1900 to 2100 hours) GMT	.11	.21	.24	97.0
DIURNAL EFFECT ON FIVE FLIGHTS DURING TWO TIME PERIODS TO THE SAME RUNWAY				
BURLINGTON RUNWAY 15				
Flight BTV 340-1	.08	.04	.09	96.9
Flight BTV 134	.08	.03	.09	96.4
Flight BTV 169 (1400 to 1800 hours) GMT	.08	.03	.09	96.4
Flight BTV 136	.08	.03	.09	96.4
Flight BTV 182-5 (2100 to 0200 hours) GMT	.07	.05	.09	97.7

TABLE 2.1-16. SEASONAL EFFECTS ON CTE FOR APPROACHES TO BTV RW15

FLIGHT	SEASON	CTE (nm)
BTV 340-1	Winter	.08
BTV 134	Spring	.08
BTV 136	Spring	.08
BTV 169	Spring	.08
BTV 182-5	Summer	.07

TDA LOP thus it is the most sensitive to changes in the propagation medium. Major temperature changes along the propagation path, as for example deeply frozen ground, cause the ground conductivity values to change. As noted previously this change is very gradual and has a period of one year.

In any particular year the actual seasonal cycle of the ground conductivity may differ significantly from the mean cycle which is the average over many years. In fact the year-to-year conductivity variations cannot be identified a priori without a 3-5 year base of data. In addition, there may also be variations within a season in a particular year. The seasonal effects observed at BTV are based on 18 months of data and may not represent the mean seasonal effect.

Table 2.1-16 indicates that no significant change in CTE was observed in the airborne data during three seasons evaluated.

2.1.5.6 Primary and Alternate Triad - The uncorrected accuracy potential of LORAN-C depends on the physical location of the LORAN-C receiver within the coverage grid. Small crossing angles introduce geometric errors as the hyperbolic LOPs become more nearly parallel. Also, when operating along a baseline extension small changes in TD's represent large distances and thus navigation accuracy degrades correspondingly. To mitigate the potential geometric error the TDL-711 receiver may be programmed to track four transmitters including the master, arranged in two different triads, as selected by the AREA switch. These triads can be from the same chain or from two different chains. For the Vermont test the AREA One switch position was programmed to select in the primary triad MWX of the Northeast chain while the AREA Two switch position permits the pilot to select the alternate triad MWY for use. In each case a fourth transmitter is being tracked as a back up; for the Vermont test Carolina Beach (Y) was used as back-up to the AREA One triad and Nantucket (X) was used as back up to AREA Two.

If during normal operations in the AREA One mode, the Master or one of the secondary stations, W or X, discontinued transmitting the TDL-711 automatically selected the transmitter in reserve, a procedure, identified as master independence. The pilot is advised of this situation by a series of

blinking decimal points on the CDU. This action indicates that the accuracy may be degraded. A flight involving master independent operation is described in detail in Appendix C.

Because of the substantially longer ground path between the Carolina Beach transmitter and Burlington VT, the MWY triad was relatively less accurate than the MWX triad unless the TDL-711 was provided a calibration value. Measurements were taken at three locations in Northern Vermont and a "one time" BTV correction found to be feasible for the entire precision range and an area of about 50 miles radius distance. When no correction was used an error typically 2.0' of latitude north and 0.5' longitude east was observed. At the survey point these values translated to 2 nm and .35 nm respectively. The major contribution to the error is the value of the constant used for the propagation velocity and its effect on the TDC LOP at the survey point. The TDC gradient at BTV is 1559 feet/microsecond and the bearing of the normal to the LOP is 129° Table 2.1-17 presents comparisons of measured AREA Two values with surveyed values prior to introduction of calibration. Table 2.1-18 shows the improvement in accuracy achieved after calibration. Two additional measurements were made in flight. The pilot overflew a NAVAID while the flight engineer compared present position with published coordinates for the aid. After the flight the aircraft returned to the surveyed point and the results were recorded. Results obtained on two flights are shown in Table 2.1-18.

2.1.5.7 Supplemental Type Certificate Requirements - The state owned aircraft was originally an Army Model U-8D. It was converted in April 1980 to an FAA certifiable commercial Model E50. This action was taken in preparation for an application for a supplemental type certificate, STC, permitting installation and use of a Model TDL-711 LORAN-C navigator. Since the Twin Bonanza installation is so unique, and very few E50 type aircraft are in existance, the application for STC will be for one aircraft only. However the performance data described in this report and submitted in support of the STC

TABLE 2.1-17. COMPARISON OF AREA 2 CALIBRATION VALUES

FLIGHT	CALIBRATION POINT	LATITUDE (deg, min)	LONGITUDE (deg, min)
BTV 045*	Survey(S)	44 27.9	73 08.8
	Area 2	44 29.9	73 08.3
	Δ Area 2 - (S)	2.0	-0.5
BTV 129**	MVL NDB	44 35.2	72 35.2
	Area 2	44 37.2	72 34.4
	Δ Area 2 - MVL	2.0	-0.8
BTV 189-2**	MPV VOR	44 12.7	72 33.7
	Area 2	44 14.5	72 32.9
	Δ Area 2 - MPV	1.8	-0.8
*Ground Calibration **Air Calibration	-2.0 min. latitude 0.5 min. longitude		

TABLE 2.1-18. RESIDUAL ERROR AFTER USING A CALIBRATION VALUE IN THE AREA 2 MODE

FLIGHT	CALIBRATION POINT	Δ LAT (min)	Δ LON (min)
BTV 045	Survey	0.1	.05
BTV 169	Survey	0.3	-0.2
Calibration values used were -2.0 min. latitude and 0.5 min. longitude.			

would be pertinent to any other application. The process for obtaining an STC is outlined in Figure 2.1-16. The accuracy data from the flight test in Vermont is the substantiating data indicated on the flow-diagram. The procedure for a second applicant with a 711 in an E50 is outlined in Figure 2.1-17. The recipient of the certificate would be the State of Vermont in this case.

The TDL-711 has already been granted one STC by the FAA. It is for use in a helicopter (BELL MODEL 212) while flying enroute in the Gulf of Mexico.

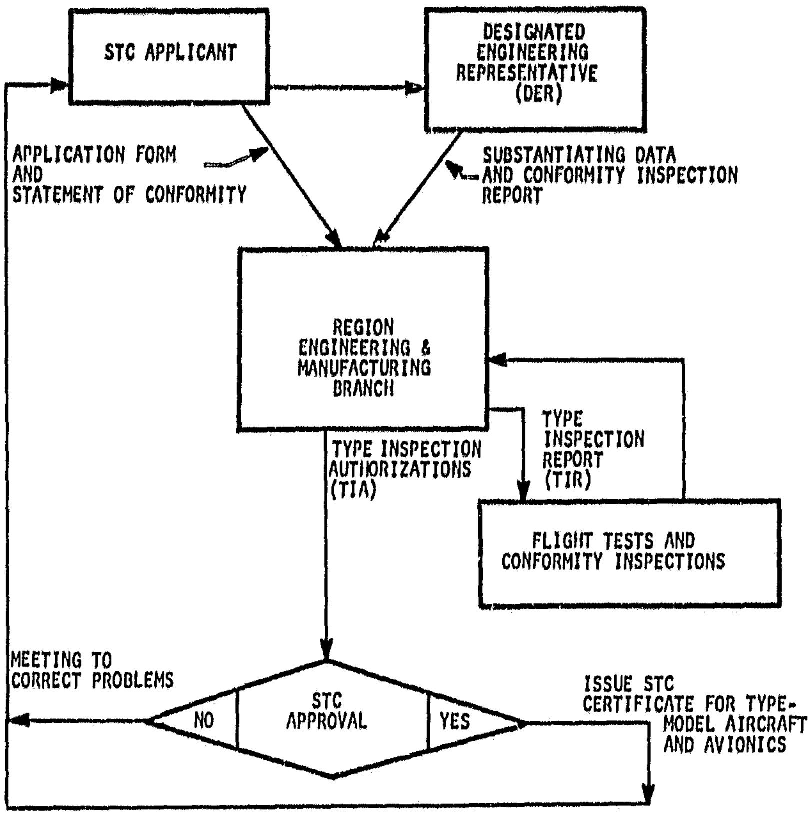


FIGURE 2.1-16 PROCESS LEADING TO A SUPPLEMENTAL TYPE CERTIFICATE

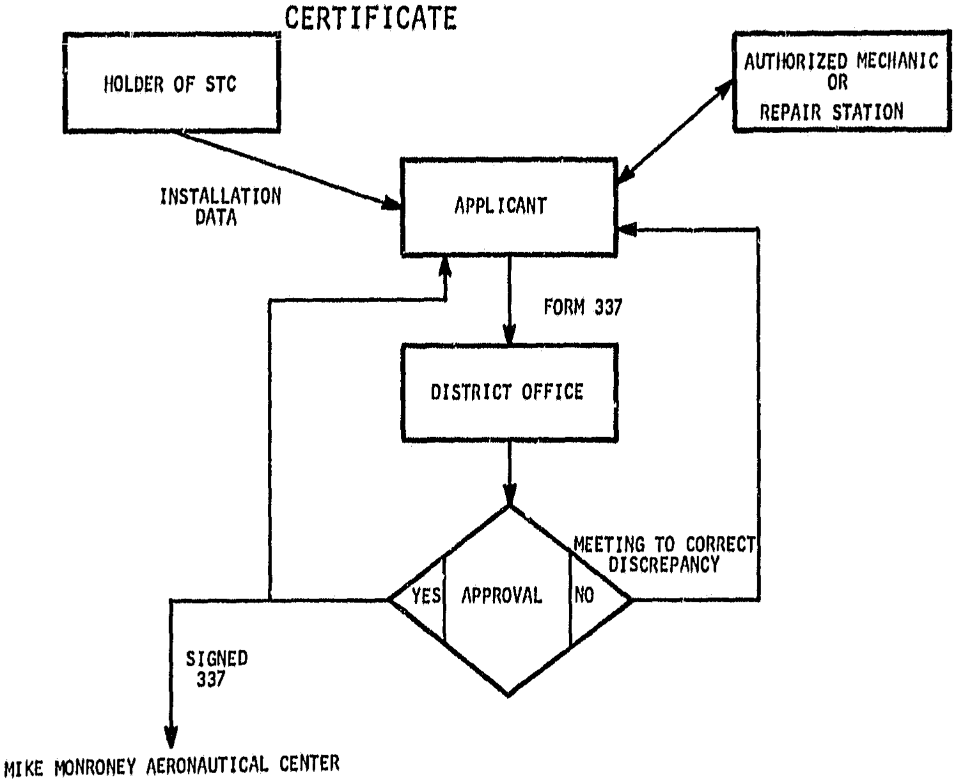


FIGURE 2.1-17. PROCEDURE AFTER ISSUE OF ORIGINAL STC

2.2 FLIGHT PROCEDURAL TEST RESULTS

The second objective of the Vermont LORAN-C test program was to identify and evaluate the procedural impact of LORAN-C RNAV on civil aviation. Procedures studied include those related to both the pilot and the air traffic control system. It is necessary to investigate the effect of LORAN-C RNAV on flight and ATC procedures to determine its compatibility with the current National Airspace System (NAS) and with requirements of the demanding aspects of single pilot IFR.

In the furtherence of this investigation 37 demonstration or procedure development flights were completed during the test period. There were official observers from organizations such as the State of Vermont Executive Office, the Agency of Transportation, DOT's FAA, USCG, and RSPA, Canada's Department of Transport, and representatives of the Directors of Aeronautics of several New England States, the New York Department of Motor Vehicles, and a representative of the State of Alaska, DOT. In addition four LORAN-C receiver manufacturers and 33 GA pilots participated in one or more familiarization, check out or demonstration flights. There were 16 flights to develop procedures for using a LORAN-C navigator in the NAS. These 16 flights evaluated holding patterns, straight in approaches and special departure routes. Other flights demonstrated the use of LORAN-C for search activities and rendezvous with ground units in remote mountainous terrain and for completing forest spraying patterns.

The following sections discuss several important differences between the use of LORAN-C RNAV and the use of conventional NAVAIDS and the methods and results of the Vermont test program that relate to these issues. It should be recognized that many of the issues relevant to the discussion of the LORAN-C navigation system apply as well to other types of RNAV equipment such as Omega, inertial, NAVSTAR/GPS and VOR/DME.

2.2.1 Background

LORAN-C provides a different form of navigation assistance from the more conventional enroute and non-precision approach guidance equipment. Its

differences are not limited to cost, technological principles or development history--although these differences may be very large. More importantly, LORAN-C provides a navigation capability to pilots and controllers which differs fundamentally in areas such as: coverage, accuracy, availability, user interface, calibration requirements, performance capability, and application potential.

To understand the differences, the services provided by conventional NAVAIDS are presented, contrasted with LORAN-C, and equivalent procedures identified. The facilities currently providing virtually all of the enroute and non-precision approach guidance are: VHF Omni-Directional Range (VOR), Distance Measuring Equipment (DME), Non-Directional Beacons (NDB), and VHF localizer facilities.

A VOR is a to-from navigation system; that is, a pilot may select either an inbound or outbound course on any radial emanating from the transmitter. The resolution of course selection and alignment is approximately one degree and therefore all airways, fixes and commands referenced to a VOR are described in one degree increments from magnetic north. The system is more than 30 years old and is required for instrument flight in the U.S.; therefore pilots and controllers fully accept and understand the system and use it extensively. In Vermont, however, only two of the nine runways with published instrument approaches are served by VOR (one of which of has a co-located DME) while two other airports offer circling approaches based on VOR/DME located 7 and 15 nautical miles distant from the respective airports.

Because it operates in the very high frequency (VHF) band VOR signals are restricted to line-of-sight propagation. Depending on the class of the VOR (terminal, low altitude or high altitude) it's range below 18,000 feet can extend to 25 or 40 nautical miles assuming no obstructions to line-of-sight. While some regions receive redundant VOR coverage, mountainous and remote areas, particularly near the surface, frequently have no VOR coverage.

Two VORs are located within the State of Vermont and three others are located at the Vermont border in New York and New Hampshire. Because of obstructions and other signal propagation difficulties, these facilities are

unusable at transition and approach altitudes at all but five airports. See Table 2.2-1.

The VOR signal is subject to propagation distortions and multi-path effects which can produce erroneous navigation information; for example, the CDI needle may on occasion oscillate, particularly in mountainous terrain or at certain propeller RPM settings. Flight testing is required to assure the quality of VOR signals in a given region. The specification on total VOR system accuracy is 4.5 degrees (95 percent confidence) which translates to a potential position error of 471 feet per nautical mile of distance between transmitter and aircraft. Frequent accuracy checks of the airborne equipment must be made either on the ground or in the air to comply with Federal Aviation Regulations for instrument flight. These checks are accomplished by noting the indicated position when located at or over a known position, through the use of a special VOR - test transmitter, or by crosschecking two receivers against one another.

DME determines the distance between the ground receiver/transmitter site and the airborne equipment by measuring the round-trip travel time of an ultra high frequency (UHF) signal. DME ground stations are usually co-located with a VOR; VOR and DME frequencies are paired so that when the VOR is selected, the DME will automatically be tuned in. Like VOR, DME coverage is limited to line-of-sight.

The DME system accuracy is generally within 0.1 nm or 1 percent of the distance, whichever is greater. This does not include the error introduced by measuring the slant range rather than the actual horizontal distance from the station.

Co-located VOR/DME systems provide a complete horizontal navigation capability. A radial and distance can be specified to define any point within the accuracy and range of the equipment. This is known as a rho-theta system since position is described by a distance (rho) and an angle (theta) relative to the transmitter. ATC uses intersections of two radials (theta-theta) or a

TABLE 2.2-1. LIMITATIONS ON VOR USAGE IN VERMONT

FACILITY	REGION EFFECTED		
	BETWEEN RADIALS (deg)	BEYOND DISTANCE (nm)	BELOW ALTITUDE (ft)
Montpelier	205-280	30	7000
Burlington	080-105	35	5400
	135-155	30	5400
	080-155	30	9000

TABLE 2.2-2. TIMES TO ENTER WAYPOINT DEFINITIONS

	ALL DATA			OUTLIERS REMOVED		
	MEAN (sec)	SIGMA (sec)	SAMPLE	MEAN (sec)	SIGMA (sec)	SAMPLE
Flight 355 Ground	35	18	9	27	07	7
Flight 362 Ground	36	18	9	27	06	7
Combined Ground				26.9	06.3	14
Flight 355 Air	41	15	7	33	05	5
Flight 362 Air	35	08	7	34	08	7
Combined Air				33.4	06.4	12

radial and a distance arc (rho-theta) to define reporting or holding fixes (rho-rho fixes are not used by ATC and few GA aircraft carry redundant DME equipment).

Localizers, when used alone, provide non-precision approach guidance or, used in conjunction with glide slope and other information, they provide the horizontal portion of a precision approach guidance. The signal is normally aligned with the runway center line and provides a 3 degrees to 6 degrees wide channel to the runway threshold. Although proper off-course signals extend 35 degrees to either side of the runway out to 10 nm, and 10 degrees to either side out to 18 nm, only one On-Course signal is indicated. There is only one runway in Vermont equipped with full precision approach; single runways at two other airports are served by Localizers and still another airport is served by a localizer-not-aligned with the runway, called an LDA approach.

The ILS localizer signal is often usable for "back course" approaches to the reciprocal runway; however, the CDI indications may be reversed from the normal VOR and localizer directions creating a somewhat higher workload and blunder potential for the pilot; this use of "back course" localizers is being phased out. Localizers, therefore, are inflexible in that they can only serve a single runway with a fixed, straight, approach course.

NDBs provide guidance for the transition from enroute to airport precision approaches and frequently serve as the primary approach guidance for many small and remote airports. Of the nine airports in Vermont with published instrument approaches, three are serviced only by NDBs,and four others incorporate NDBs in their terminal and approach procedures. Since NDBs operate in the low and medium frequency band, these signals can reach many locations not within line-of-sight. Transmitter power varies among installations so that service ranges of from 10 to 350 nm are experienced. Equipment accuracy is approximately 3 degrees. It is noted here that all of the NDBs situated in Vermont are low radiated power facilities thus are relatively short ranged.

NDBs provide relative directional information rather than track definition (as a VOR does) thus compensation for crosswind component of wind is more difficult. A pilot may home on a NDB or through the use of magnetic heading even fly a given radial to or from the transmitter. The mental workload required of the pilot when using the NAVAID precludes it from playing a major role in the enroute airway system. In addition, compass inaccuracy and instability may add an additional 5 degrees to the equipment error. For approach guidance, an NDB may be restricted to only moderately low minimum descent altitudes (MDA) and circle-to-land approach procedures. These restrictions adversely affect airport utilization; for example, at Newport, Vermont the circle-to-land approach includes an MDA of 1640 to 2020 ft, while the LORAN-C straight-in approach permits the MDA to be lowered to 1420 ft.

<u>LORAN-C</u> used in conjunction with RNAV computers can provide either a to-from navigation system similar to VOR, or a to-to system, as is the case in the TDL-711. The 711 requires two waypoints to define a course; this course is a great cicle path between the waypoints and thus navigation is always, outwardly, based on flying to the next point; that is, one cannot set up a radial and fly away from WP, although it is possible to achieve the same end result by proper use of the equipment. Navigation can be continued on the line extending through the two waypoints even beyond the fix itself,if the situation so dictates.

The 711 system accepts waypoints which are defined either as LORAN-C Time Differences or as True Latitude and Longitude coordinates. The pilot is permitted to enter the coordinates of any two positions or of aircraft present position plus waypoint and then either fly a direct route between them or he may maneuver randomly with respect to (i.e., on ATC vectors) the steering commands. These positions can correspond to conventional NAVAIDS, intersections, airports or any impromptu positions defined by the pilot or ATC.

LORAN-C operates in the low frequency RF band and therefore is not hindered by topography or other line-of-sight limitations. Its transmitting power is sufficient to provide coverage over hundreds of miles, including remote areas, and rugged terrain. Its accuracy, as discussed in Section 2.1 was demonstrated to be more than sufficient for use both as an enroute and a

non-precision approach facility. Propagation, anomalies, terrain, seasonal and other effects could require the use of calibration procedures at other locations and times; generally, however, the Vermont flight tests indicated that the temporal variations were sufficiently small that calibration was not needed to meet AC90-45A accuracy requirements when using the primary triad. On those occasions when the transmitter at Carolina Beach was substituted for Nantucket and calibration values were used, enroute and approach navigation continued to meet the AC requirements.

2.2.2 Methods of Data Collection

Data related to operational acceptability of LORAN-C RNAV in the civil aviation environment was gathered through interviews and reports completed by the GA pilots who participated in the demonstration and familiarization flights. This information was included with the "Mission Complete Reports" prepared for each of 104 RNAV evaluation flights.

Four primary data sources available from the test program were: in-flight electronic recording of the parameters shown in Table 2.1-2; mission-pilot and flight engineer written reports providing a chronological background of information, general comments and procedural observations for each flight; recordings of LORAN-C signals received on the ground at Burlington International Airport; and LORAN-C station logs provided by the U.S. Coast Guard.

The detail provided by the inflight electronic data recording permits a relatively complete reconstitution of the information available to the pilot, evidence of which parameters he was viewing at any time, the time of 711 CDU switch operations, and his general utilization of the equipment. The ground recordings and the USCG station logs provided information about operation of the LORAN-C transmitters.

2.2.3 Results and Conclusions

The Vermont test program permitted observation of the suitability of LORAN-C RNAV in all phases of flight and in many strenuous and unusual environmental and aircraft flight conditions. Surprisingly few significant RNAV system problems were encountered during the 104 flights; however, the events of two flights (BTV 355 and 362-1) described in detail in Appendix C give useful insight to difficulties which can be experienced on occasion. From data collected for these two and the remaining 102 routine flights, conclusions are drawn regarding the operational suitability and procedural implications of using LORAN-C RNAV for civil air navigation.

2.2.3.1 LORAN-C RNAV Compatibility with ATC Procedures -- Safe and efficient flow of traffic depends in large measure on the ATC system facilities as they are and proper use of standardized operating procedures which controllers and pilots follow. The current ATC and cockpit procedures have evolved with growth of the present VOR/DME and radar surveillance systems. The airborne and ground base systems, despite some shortcomings, account for a majority of enroute guidance. The VOR/DME system, together with NDBs and localizers, provide the system's non-precision approach guidance. Procedures are, therefore, revolutionary in nature and tailored to meet the requirements of these existing, 30 year old systems and are not necessarily compatible with the most efficient or practical uses of a LORAN-C RNAV system.

a. LORAN-C in the Present ATC System -- The current ATC system uses VOR/DME as the primary navigation system; the airborne navigation equipment must enable the pilot to accomplish the following:

- fly to the location of a VOR on a given radial
- fly from the location of a VOR on a given radial
- identify aircraft position as a radial and distance from a stipulated VOR/DME facility
- identify position with respect to the intersection of radials from two VOR facilities
- fly directly to a VOR from the current position by the shortest route

- fly along charted airways, identifying and reporting position with respect to distance along route and intersection location
- "hold" along a VOR radial at a fix defined by an intersection or distance from a VOR/DME

In its simplest form VOR/DME is a to-from system of navigation whereas the TDl-711 LORAN-C receiver is a to-to "homing" system designed to minimize workload when operating on airways or in patterns relative to a specified facility. Without an RNAV computer off-airway operation imposes a sharply increased workload. The TDL-711 is designed for off-airways operation and thus the pilot must become familiar with new procedures, not necessarily straightforward, in order to fully satisfy the ATC tactical requirements listed above. However, with a bit of study and some advance planning, the 711 can fully meet these requirements with a high degree of precision and without imposing undue workload.

Any point or path defined in a to-from system can also be defined in a to-to system, conversion from rho-theta to rectangular coordinates (latitude and longitude) can be performed graphically or by using a calculator, or can be supplied on charts or in computer memory. For routes defined by a "from" radial, (such as those often found on Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs), a pair of waypoints could be depicted on charts. Holding patterns can also be defined by a pair of waypoints, as, for example, note the HERRO-CAUSS Holding Pattern included on the BTV LORAN-C Runway 15 approach (Figure 2.2-1). With this additional waypoint information made available to pilots, all requests made by the current ATC system can be met.

While it may seem operationally difficult for a controller to supply the geographical coordinates of a fix selected on an ad hoc or impromptu basis, the future use of advanced ATC computers suggest that some flexibility in this area may eventually be available. Until then on those occasions when a controller must ask a pilot to report crossing a radial from a VOR or to hold on a radial at a point not charted as a holding location, the procedures

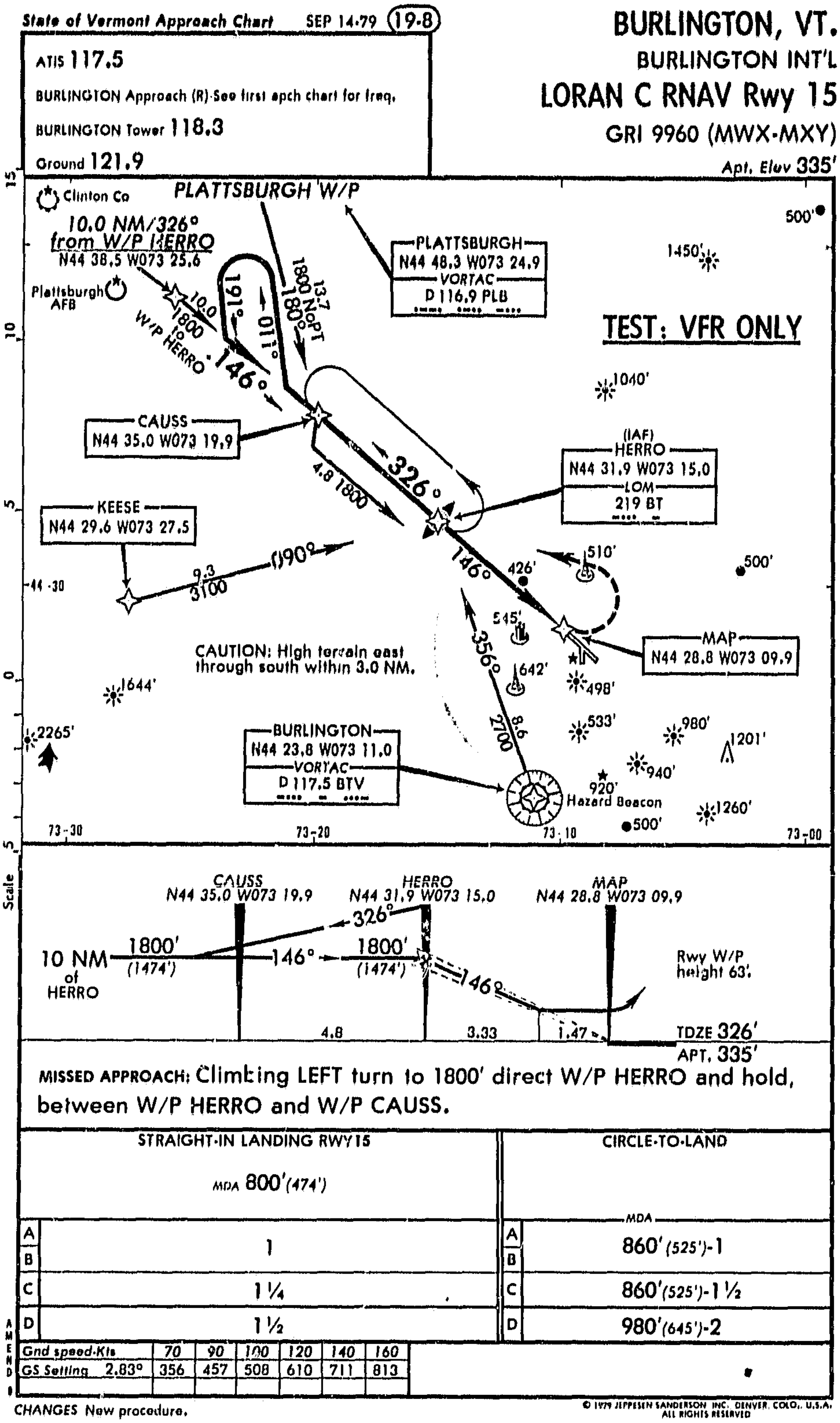


FIGURE 2.2-1. LORAN-C APPROACH TO RUNWAY 15 AT BURLINGTON INTERNATIONAL AIRPORT

described above offer a viable solution. In the future, ATC may have the capability to define RNAV waypoints by coded units of latitude and longitude as, for example, 44° 00.0' N 73° 00.0' W, perhaps characterized simply as 44/73.

b. Expanded Service: Future Uses and Benefits -- The TDL-711 RNAV system provides capabilities which could ultimately lead to increased capability in enroute and terminal airspace while at the same time reducing controller workload. The operations in Vermont during the 18-months long flight program have indicated the possibility of providing additional departure and arrival paths, straight-in approaches, improved holding patterns, enroute-direct and traffic reliever routes, which will increase the safety or efficiency of the National Airspace System. The ability to define impromptu fixes, fly direct to any given fix, and fly a parallel course offset from the parent course by a specified amount all enhance the performance of today's ATC system.

LORAN-C RNAV permits shorter, more direct routes to be flown, gives the controller increased flexibility in separation and sequencing of traffic, allows for reduced minima at many airports, provides instrument approaches to many more runways and reduces controller workload. Any number of holding patterns can be defined to meet current needs. During flight BTV-169, several holding patterns were flown in the Morrisville area using existing waypoint definitions and offset values; this saved data entry time and provided the navigation information required. In addition, it assisted the pilot in maintaining position in the holding pattern despite excessive drift due to a 40 knot crosswind (this has been a problem on many previous flights).

Parallel offsets can be used for many purposes; often their use will replace an equivalent series of radar vectors. Traffic conflicts, weather avoidance, aircraft spacing, restricted airspace avoidance, flight path reduction, and many other circumstances require radar vectors from ATC. While radar vectoring usually requires that the controller issue several commands to accomplish the spacing he is trying to achieve or to feed an aircraft into an

approach before releasing it to its "own navigation", the same end might be accomplished by allowing the RNAV-equipped aircraft to perform self-directed maneuvers utilizing the very accurate parallel offset mode. This procedure could sharply reduce communications traffic and controller stress.

The capability to fly "direct" to any defined waypoint can also replace radar vectoring presently used in some terminal areas to assist the pilot in expediting entry to final approach. Moreover, the LORAN-C RNAV capability will permit definition of more direct routes thereby shortening trip distance, saving fuel and reducing operating costs. RNAV capability could give controllers more flexibility in routing aircraft around areas of bad weather or heavily congested areas. SIDs and STARs can be made more efficient and more flexible allowing for less costly sequencing and spacing maneuvers to be prepublished and for changes to be made to landing runway during execution of a STAR.

Definition of LORAN-C RNAV fixes at appropriate locations where no aids now exist could permit straight-in approaches to many runways not presently served by any NAVAIDS or to those which presently offer only circle-to-land approaches. Better missed approach guidance can also be provided for many airports such as Rutland, VT where mountains interfere with VOR reception and the only navigation aid is an NDB. Both of these improvements may lead to lower minima at many runways and thus will provide improved service to the aviation community and remote population centers.

c. Approach Procedure Development -- Before public LORAN-C approaches can be approved a set of guidelines for their development and specification must be prepared and made a part of the FAA Terminal Instrument Procedures (TERPS).

Each approach will require selection and designation of a minimum three waypoints: Final Approach, Runway Threshold and Missed Approach. Enroute and transition waypoints may be used for more than one approach and also for departures. Each runway will have a missed approach point (MAP) defined either by a WP or by the along track distance readout, preferably the latter, to indicate the location at which the decision to land or to abort must be made. The course and distance solution for final approach will be defined

(for the RNAV system) by the Final Approach and Runway Threshold waypoints. Additional waypoints may be assigned, i.e., initial approach and intermediate approach waypoints but only if there is some special need like a turn in the approach. LORAN-C offers the possibility of segmented and angled approaches to runways blocked by obstructions which could result in use of additional waypoints, i.e., WILEY and BLAKE on the Morrisville Approach. Each instrument approach is designed with a missed approach procedure which is initiated if, upon reaching the MAP, the runway is not visible to the pilot. One or more waypoints may be specified to assist the pilot in avoiding hazards while climbing to a safe altitude. The procedure returns the pilot to a point from which another approach can be made if he so elects, or alternative action may be taken.

Until the introduction of LORAN-C RNAV all missed approaches in Vermont were designed around the available terminal navigation aid. This often results in the missed approach including undesirably abrupt maneuvers as the 180 degree turns at Rutland and Morrisville. During the LORAN-C RNAV project new departure and missed approach procedures were evaluated. At Rutland, for example, the present instrument departure and the missed approach are to the north over the IRA NDB. During the test a flight path to the south was evaluated which appears to allow for improved minimum on approach, a much improved missed approach procedure, and a more reasonable departure for all south-bound traffic. There is reason to believe that successful implementation of this south-bound departure route will reduce delays at the airport and will materially improve operating costs.

The ability to essentially stick waypoints wherever needed, at no compromise to accuracy of navigation, is felt to be a major advantage of LORAN-C. Additional waypoints can be useful in providing alternative transition routes between enroute and approach phases of flight or to provide alternative paths for use by aircraft of differing performance or to allow controllers more flexibility in sequencing and separating traffic.

The stability of grid bias has been determined to be such that LORAN-C approach charts could contain all navigation information which would be required when an aircraft entered a particular region. For example the approach minima might depend on whether the primary triad or the alternate

triad is utilized. As an alternative to using published data air traffic controllers could relay the data while transmitting approach clearances. A second alternative is to permit calibrations for the alternate triad to be made on the ground anywhere within a given distance of the destination airport as long as it is within the same triad. In the long term it is assumed that secondary phase correction data, the problem which leads to the need for calibration, will be permanently stored in RNAV system memory and thus be totally transparent among users, minimizing the possiblity for blunder, and reducing workload. (This is a feature that will be designated into the FAA's low-cost receiver.)

Procedures for handling transmitter outage will also be required. While there is some transmitter redundancy in the system, use of alternative configurations will require introduction of different bias corrections, calibration values, or parallel offset quantities to cope with local anomalies. If an alternate triad is used, it may be necessary to raise minima.

Since the TDL-711 requires from 10 to 20 seconds to complete its internal confidence check following a re-ordering of the transmitters in a triad (when keyboard entry is used), some special procedures may be required during final approach in the event of loss of navigation (steering) data. A momentary interruption, even though only of 20 seconds duration, when at one mile on final approach could be considerably more serious than a similar event while enroute.

2.2.3.2 Cockpit Procedures -- The effect of LORAN-C RNAV on cockpit procedures is a critical issue. It is essential that use of the system will not increase pilot workload and, thereby, the chance of a blunder or reduced piloting performance. Requirements for retraining and limitations on use of the system must be determined. Various new regulations, charting requirements, training programs, and piloting techniques may be necessary. The Vermont test program has addressed these questions; a discussion of new cockpit procedures and pilot workload follows.

a. Waypoint Determination and Entry -- The 711 LORAN-C RNAV receiver accepts waypoint definitions in either TD coordinates or latitude and longitude (L/L) coordinates. Both of these are vastly different and unfamiliar to a pilot trained and experienced in using VOR/DME. Identification and entry of fixes with respect to these coordinates create certain difficulties as well as opportunities.

While aeornautical charts such as SIDs and STARs display the latitude and longitude of various fixes, standard approach plates and enroute charts generally do not. For a LORAN-C RNAV to be compatible with VOR/DME, the locations of fixes must be specified precisely; the location that a pilot might determine by reading the scale of a chart is not reliable or consistent enough given the errors introduced by this method as well as the inaccuracy of printed charts.

Even if all commonly used fixes are published with latitude and longitude, it might still be difficult for a pilot to determine the coordinates of an ad hoc fix. It is far easier to visualize flying along a radial from a charted VOR than along a route defined by two points on the globe.

In addition, the entry of L/L coordinates requires a string of 15 keystrokes consisting of one for east/west and north/south, five digits for each coordinate, and three uses of the "enter" key. Before this information can be entered on the keyboard, a selector knob must be turned to the appropriate position. This data entered will uniquely identify any point on the globe (to a certain precision). This permits a great deal of flexibility in determining the fix selected; however, it imposes a burden on the pilot. Furthermore, a string of digits is difficult to remember and to verify. A fix identified by name, whose coordinates are stored in memory, is at least easier to enter, verify, and remember. Furthermore, an erroneous character is likely to produce an unrecognizable name and will therefore be rejected.

The resolution of L/L entry with the TDl-711 (i.e. 0.1') may be insufficient for some approaches. To define a waypoint more accurately for the purposes of an approach would require another digit(s) and create even higher demands on the pilot. To achieve the additional precision without

adding complexity, the parallel offset feature may be used to adjust a course slightly and define a track that falls between two grid points. This technique was used with a great deal of success for approaches to RW15 at Burlington, where a 0.05 nm offset to the right was found to be appropriate. Preprogrammed fixes could, of course, be specified to any desired degree of precision.

The task of waypoint definition is greatly simplified by the capacity of the 711 to store up to nine fixes at a time. This enables the pilot to enter the data for all or most of the flight on the ground in an unhurried fashion. With some forethought, a complete set of fixes for any difficult portion of a flight, such as approach and missed approach, can be defined during a less demanding time. Training and regulation should emphasize the value of setting up the required and contingent fixes before they are needed. This will relieve much of the burden imposed by the L/L coordinate system. Under current ATC procedures, a typical point-to-point flight will not require any inflight waypoint entry or at most one set might be entered midway through the flight. In the future, however, when ATC begins to take full advantage of RNAV capability, many contingent waypoints may be specified for spacing purposes; this may increase the requirements for waypoint storage capacity. For the time being nine is sufficient but fewer might impact workload significantly in some circumstances.

To further enhance the performance of LORAN-C RNAV, the locations of all VOR/DMEs and other important waypoints such as final Approach Fixes and Missed Approach Points, should be prestored and referenced by a 3 to 5 letter code.

Furthermore, it should be possible for the user to define waypoints in the form of a distance and bearing from any known point. The distance and bearing between any two points defined should also be displayed on request to verify the location of the waypoints. The best solution of all is the CRT displays now being used in advance cockpit designs. These will permit the paths defined by the waypoints to be displayed in relationship to known locations including VORs, airports and terrain features. It may also be possible to define waypoints through interactive use of these displays using a light pen of other data entry device.

b. Pilot Workload -- For LORAN-C to be an acceptable navigation system it must be demonstrated that neither the workload it places on the pilot nor the potential for blunders is excessive. Many differences exist between waypoint entry in latitude and longitude versus a rho-theta coordinate system such as VOR/DME. Some of these differences are an advantage while others increase workload or blunder potential.

Because latitude and longitude are global coordinates they can be entered and stored in computer memory independently of station selection. A VOR/DME coordinate is a local coordinate that must be referenced to a given station, identified by its three letter code or its frequency. The ability to set up the majority of the waypoints for a flight while on the ground and the remainder during a relaxed portion of the flight relieves the pilot's workload tremendously. Furthermore, it shifts the burden from times determined by navigation requirements, often high workload periods, to more convenient times of the pilot's choosing.

The most serious drawback of the L/L form of waypoint specification in the TDL-711 is the potential for blunder. This arises from several characteristics of this form of specification not found in VOR/DME. First, the entries are made digitally rather than through a continuous (albeit click) dial. This makes the transposition or erroneous entry of a single digit potentially very serious. An error in a single digit can cause an error of several degrees of latitude or longitude. While this is so gross an error the pilot might soon recognize it, errors in less significant digits would produce serious but less easily detected errors.

Another possible blunder arises from the use of multiple-position switches and multiple use display. During one flight (BTV-113) the pilot attempted to enter waypoint information while the selection switch was on the magnetic variation mode. This points out the potential for entering data or interpreting displayed data incorrectly because insufficient physical clues indicate the mode of the selectors and displays.

On several occasions a leg change was made incorrectly by entering one or more incorrect waypoints (e.g., BTV-045). Although the incorrect distance and bearing to the next waypoint indicated the error, the pilot might not verify the selection by this means under difficult situations. Since this is currently the only means to verify the validity of the next waypoint it may be advisable to display current track and distance to go continuously on the CDI itself.

The time required to enter a waypoint and to enter waypoint changes is an important indication of workload. Although the data available from the Vermont test program do not include time spent looking up values, they do at least indicate the length of time required to enter the data and the frequency of errors.

Figure 2.2-2 is a frequency distribution of the time to enter leg changes (the waypoint numbers) for one pilot on several flights. This distribution is roughly normal with:

mean (x) = 11.35 seconds
standard deviation(s) = 3.74 seconds
number of samples (n) = 100 samples

The few high values for 18 to 24 seconds are most likely due to input error which was corrected immediately. There are seven of these values so approximately 7 percent of the waypoint changes had to be entered twice due to error.

The times to enter waypoint definitions were also measured both on the ground and inflight. Statistics from two flights were calculated for these values both with and without the values corresponding to entry errors -- these are shown in Table 2.2-1.

While the results from the two flights are quite consistent there appears to be a difference between air and ground entry times. Using a Student's test of significance, we find that, with outliers removed, the difference between ground and airborne measurements is significant to the 99 percent level. It

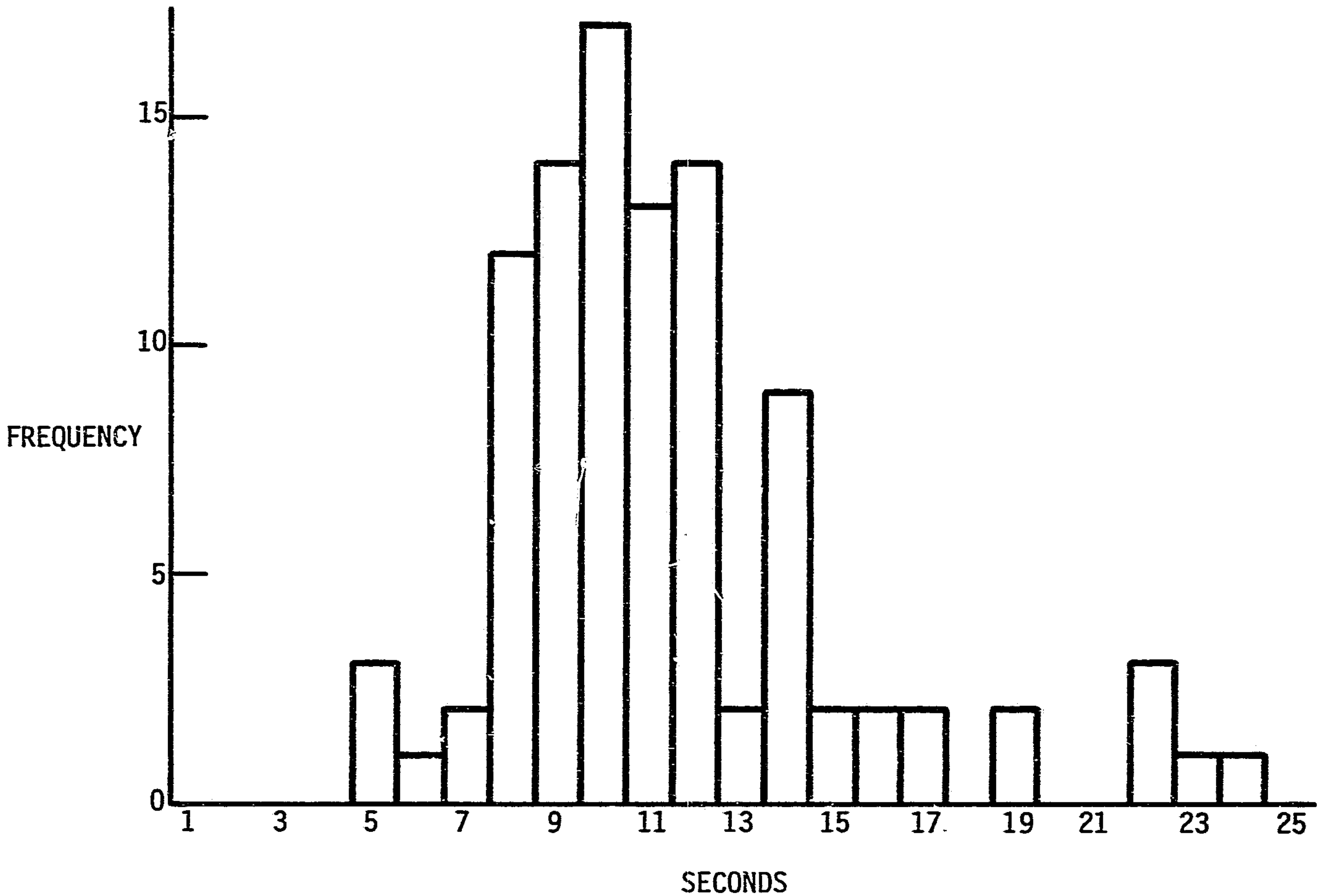


FIGURE 2.2-2. FREQUENCY DISTRIBUTION OF THE TIME TO ENTER LEG CHANGES

is also noteworthy that 4 of 18 ground samples were outliers, indicating that errors in data entry are made, and corrected, approximately 22 percent of the time on the ground and 14 percent in the air. Certainly differences will be evident between pilots of varying skill and familiarity with the equipment. Differences are also expected between flights conducted under varying levels of stress created by ATC and weather conditions.

Several test flights conducted in a Cessna Turbo 210 aircraft focused primarily on the evalauation of enroute operations and procedures. Both the New England and Great Lakes LORAN-C chains were used in providing the opportunity to study transitions between chains as they affect cockpit procedures.

The pilots involved in this study agreed that the LORAN-C provided "significant reduction in workload, increased ease in locating airports (like Manassas, VA which has no NAVAIDS), better track keeping performance and more time for outside-the-cockpit-scans...". Generally all waypoints were programmed prior to takeoff and in many instances the destination airport was called up as the to waypoint immediately upon becoming airborne.

It was also found that ATC was very cooperative in providing "direct" clearances from airports to distant NAVAIDS. For example, a direct routing from Burlington, VT to Delancy, NY, 166 miles west, was issued frequently. Operations from Portland to Burlington were almost always cleared direct from runway to runway. Even in the New York City area, ATC was willing to permit portions of the flights to be flown direct rather than on established airways.

2.2.3.3 Signal Quality and Implications for Flight Procedures -- Probably the most important issue concerning any navigation system is the quality of the signal throughout space and time. Before it can be relied upon to guide aircraft under actual instrument conditions, extensive studies must be made throughout the coverage area to be certified, and over a time period that encompasses all conditions that might be experienced during actual use.

In Section 2.3.2.1 figures were presented that indicate that LORAN-C coverage is available throughout the region of interest, that the signal was interrupted only briefly and on relatively few occasions, and that accuracy is within the allowed tolerances.

2.3 GROUND-BASED LORAN-C SIGNAL MONITORING RESULTS

Within the groundwave coverage region, LORAN-C is capable of providing any user having appropriate receiving equipment with a predictable accuracy of 0.2 nm (2 drms) or better (Reference 3), which will satisfy the accuracy requirements of AC90-45A for all phases of flight. To certify that the LORAN-C RNAV system does indeed meet these requirements in Vermont, specific LORAN-C signal properties were examined by ground-based monitoring. Monitor requirements were determined by analyzing characteristics of LORAN-C performance with respect to the requirements of an air navigation system, as described in Appendix A.

2.3.1 Objectives of Ground-Based Signal Monitoring

The purpose of the ground-based signal monitoring program was to acquire a data base describing operational and technical characteristics of LORAN-C signals at inland and mountainous areas. Although the specific data gathering was concentrated in Vermont, the data base itself will be applicable to similar inland regions.

One objective of the ground-monitoring effort was to evaluate the characteristics of LORAN-C signals in the electromagnetic (EM) noise and interference environment of typical airports. A second objective was to investigate the predictability of LORAN-C time difference variations (i.e., the repeatability and magnitude of "bias" or "grid error") at particular geographic locations. An understanding of the grid error is necessary to demonstrate the LORAN-C system's capability to satisfy non-precision approach requirements. A third objective was to determine the nature of temporal changes in the LORAN-C signal over the short and long term at various locations within the coverage areas of the triads being used. The final objective was to assess the reliability, availability, and stability of the LORAN-C signals for airborne applications. Based on the foregoing objectives the ground-based testing was designed to quantify the following:

1. Signal availability
2. Signal strength
3. Noise and interference
4. Propagation anomalies
5. Envelope-to-cycle difference (ECD)

These characteristics can be related to the outputs of a stationary ground-based receiver, as shown in Table 2.3-1. Note that from the table some of the observable quanties obtained from the ground-based receiver are related to more than one signal characteristic. This makes the relationship between the measured quantities and the desired parameters somewhat complicated, as discussed in the next section.

The data gathering effort involved monitoring and recording LORAN-C signals in close proximity to ground-air communication and navigation facilities. The ground tests also provided information concerning the temporal stability of the signals, thereby permitting an assessment of the ability to accurately predict time-difference coordinates for sites near the airport. In addition, an assessment was made of the variability in LORAN-C time-difference coordinates at the selected locations. The availability of in-tolerance LORAN-C signals necessary to support air navigation was assessed by examining the USCG's logs for the Northeast LORAN-C chain .

The accuracy of LORAN-C navigation is primarily influenced by propagation anomalies. To fully meet AC90-45A area navigation accuracy requirements during the approach phase of a flight, the total combined effect of uncompensated propagation anomalies and receiver errors (root sum square (RSS)) must not exceed 0.45 nm, 2 drms, with a probability of 98.2 precent.

To establish the magnitude of allowable time difference errors for operations in Vermont, consistent with this performance specification, the geometric effects of signal gradient and LOP crossing angle must be accounted for. Consider worst case geometry conditions for the primary triad (Seneca, Caribou, Nantucket) encountered at the ground data collection sites. From

TABLE 2.3-1. RELATION BETWEEN RECEIVER OUTPUTS AND SIGNAL CHARACTERISTICS

	SIGNAL CHARACTERISTICS				
RECEIVER OUTPUTS	SIGNAL AVAILABILITY	SIGNAL STRENGTH	NOISE AND INTERFERENCE	PROPAGATION ANOMALY	ECD
TD				X	X
SNR NUMBER		X	X		
TRACKING MODE	X	X	X		
BLINK INDICATOR	X				
ENVELOPE TRACKING NUMBER					X

Table A-7, it is seen that the smallest LOP crossing angle, Ø, is 43 degrees and the largest gradient, G, is = 739 feet/microsecond. Assuming that these worst case conditions occur simultaneously, it can be shown that the 2 drms position error, r_e, can be related to the one-sigma TD error, σ_{TD} by

$$r_e \approx (4.1)\ (739)\ \sigma_{TD}$$

$$r_e \approx 3030\ \sigma_{TD}$$

For the allowable 2 drms error of 0.45 nm (2727 ft) corresponding to AC90-45A approach requirements, the allowable standard deviation of the TD error, σ_{TD}, for primary triad operation in Vermont is

$$\sigma_{TD} = 900 \text{ nanoseconds}$$

It is assumed in Appendix B that a minimum performance airborne receiver will have a one sigma jitter measurement error, σ_n, of 150 nanoseconds or less, which is consistent with the design described in Reference 5. Then the allowable one-sigma propagation anomoly error, σ_{PA}, can be determined from

$$\sigma_{PA} = (\sigma_{TD}^2 - \sigma_n^2)^{1/2}$$

$$\sigma_{PA} = 887 \text{ nanoseconds}$$

2.3.2 Test Equipment Configuration

The four ground-based LORAN-C data gathering systems were provided by NASA LRC and DOT TSC. This section describes the two configurations of equipment used in the project, one of which included a TDL-711 RNAV system and instrumentation package installed in a NASA-supplied trailer and a second configuration which utilized 3 Micrologic receivers packaged with recording devices and located in office facilities at three airports.

2.3.2.1 Trailer Site - The NASA-supplied TDL-711 ground based data gathering instrumentation package was designed, fabricated, and installed in a NASA-supplied trailer by Langley Research Center personnel. The trailer was

parked in a protected location in an alert hanger at Burlington. The facility became the base of operations for the test program. All GA evaluation pilots, and participants in demonstration flights received instruction and preflight briefings in the operations trailer. The instrumentation system installed in the trailer was a replica of the airborne package installed in the E50 aircraft and permitted hands-on training for familiarization with the E50 711's operations prior to flight. Navigation charts, maps, and approach plates were provided for familiarization of flight personnel with route of flight and planned approach procedures prior to flight.

The Vermont flight test engineer was responsible for replacement of the data tapes on the incremental recorder, maintenance of an operations log, and servicing of the 711. The system recorded the same LORAN-C parameters as the airborne unit. Initially, the ground system was adjusted to record data once a second during the time of flight and once a minute at all other times. In December 1979 it was decided that a one minute increment and continuous recording would provide a sufficient data base for analyzing signal characteristics.

2.3.2.2 Airport Monitor Sites - The TSC-provided Micrologic stationary LORAN-C monitors were installed at Burlington, Newport and Ruland airports,three of the five were involved in the terminal and approach procedural and accuracy evaluation of flight activities (See Figures 2.3-1 and 2.3-2). This arrangement allowed for direct comparison of ground-monitored and airborne data. Burlington is a desirable site for ground monitoring because it is a major airport equipped with VOR/DME, ILS, NDB, marker beacon, control tower and RAPCON communication facilities, and radar equipment, and therefore offers a representative electronic nvironment. In addition, there are three radio and two TV commercial broadcast and telecommunications hub facilities. Newport and Rutland were chosen in part because of the proximity of mountainous terrain and in part because of their importance to general avaition in Vermont. For each monitor site, the groundwave propagation path involves a number of contrasting geological features which affect propagation velocity. Weather conditions range from warm summers (90 $^{\circ}$F) to very long, relatively cold, snowy winters (-30 $^{\circ}$F).

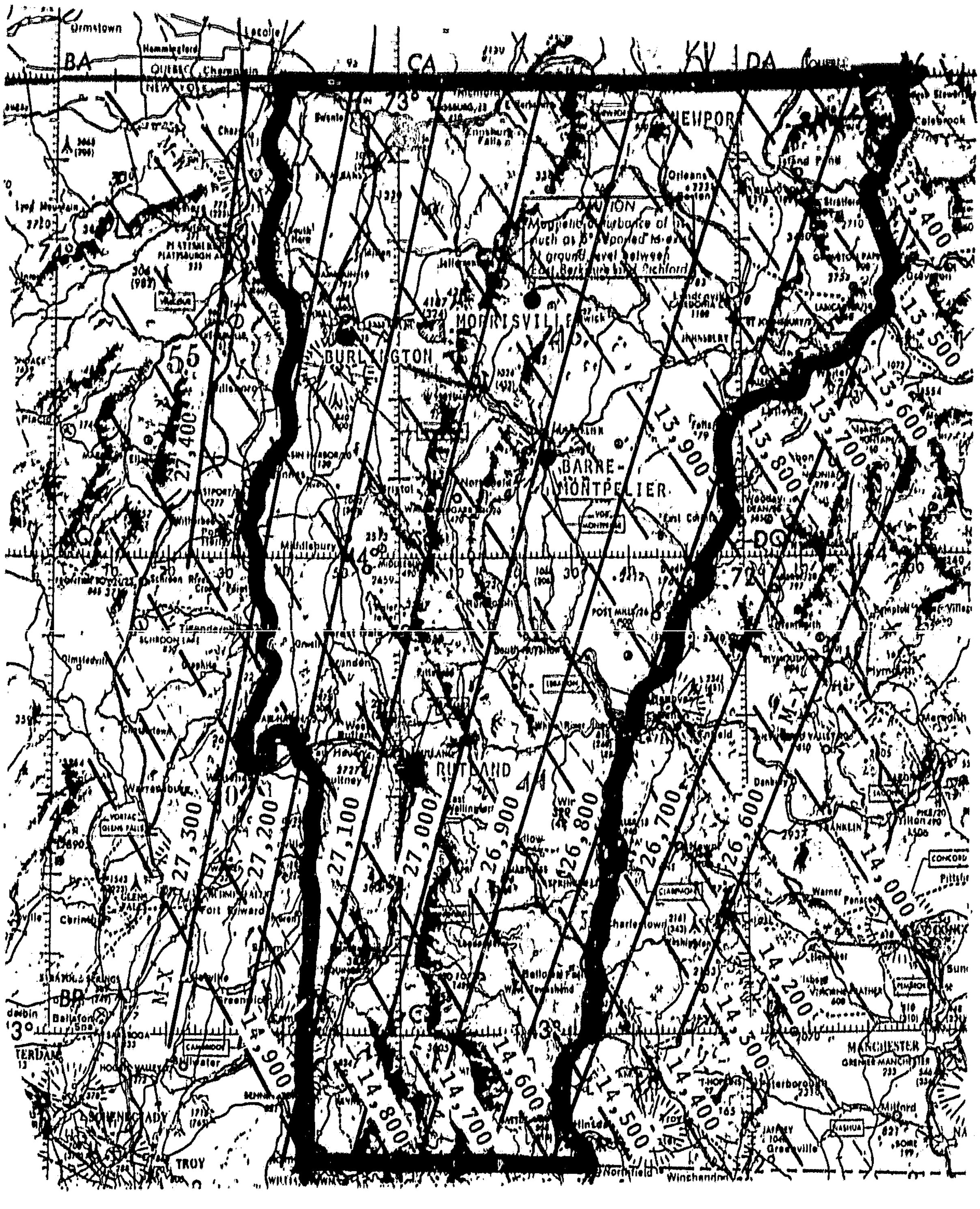


FIGURE 2.3-1. TIME DIFFERENCE CONTOURS OF PRIMARY LORAN-C TRIAD (MWX)

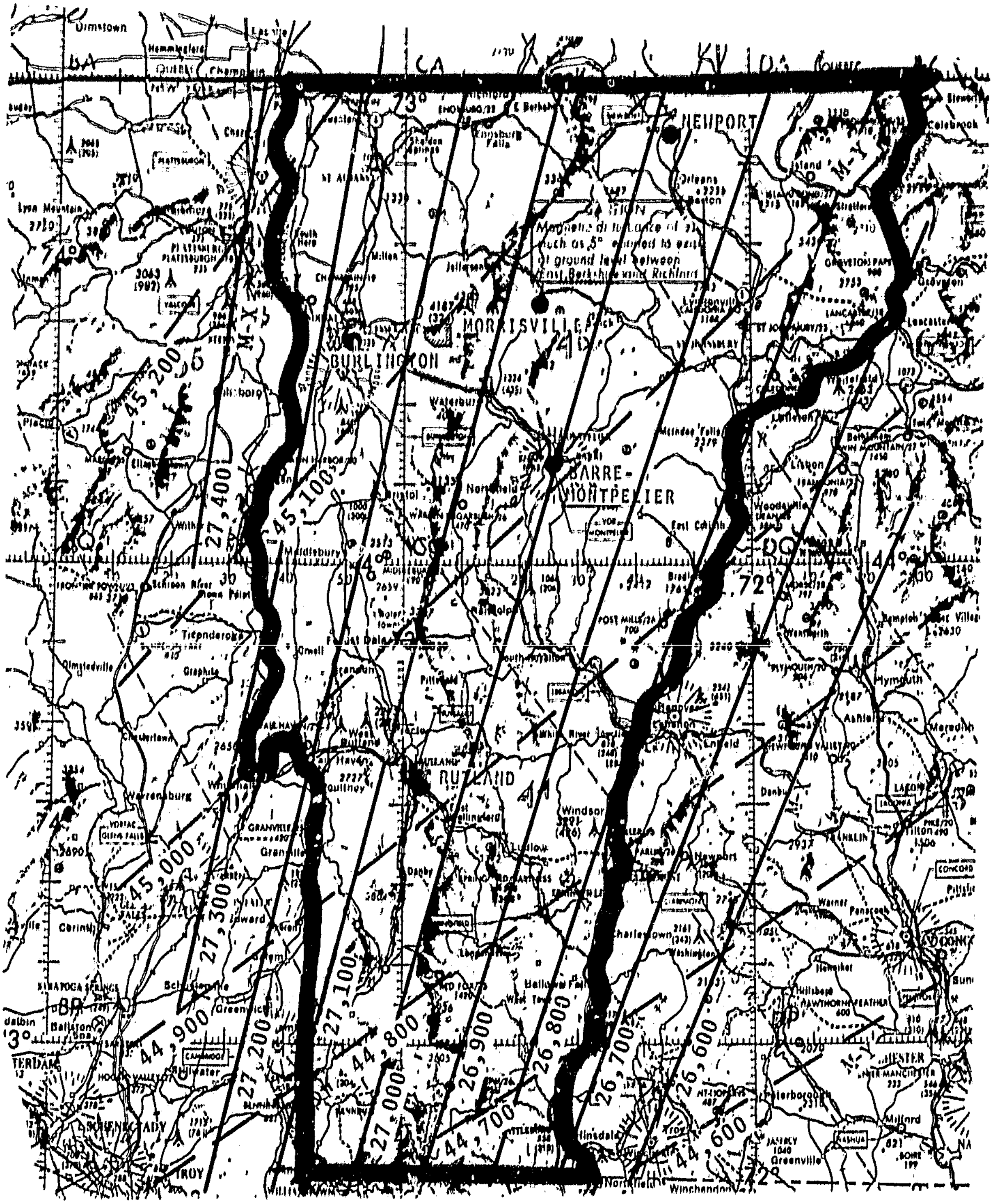


FIGURE 2.3-2. TIME DIFFERENCE CONTOURS OF ALTERNATE LORAN-C TRIAD (MXY)

A schematic of the monitor equipment installed at the three airports is shown in Figure 2.3-3. Micrologic ML-120 receivers were used to monitor the LORAN-C signals. The Micrologic receivers were modified to provide data in a serial ASCII data stream, formatted for a standard RS 232 data communication interface. An interface adapter then converted the data to frequency shift keyed (FSK) tones that were recorded on a Sony TC-104 cassette recorder. Initially, a single data sample was recorded every 30 minutes but later in the program the output was changed to a burst of 10 data samples recorded every three hours. Cassettes were replaced every other day by local volunteer personnel who forwarded the recorded cassettes to TSC for processing.

Each data sample consisted of:

1. TDs in microseconds
2. Signal-to-noise ratios (SNRs)
3. Tracking-mode numbers
4. Blink indicators
5. Envelope-tracking numbers

The outputs correspond to the LORAN-C signal characteristics as shown in Table 2.3-1.

The ML-120 goes through three basic phases of operation:

1. Acquisition - The receiver searches for the proper pulse groups, identifies the master, and starts tracking the pulse envelopes.

2. Tracking - Tracking of the RF zero crossing is established.

3. Low SNR - After track has been established, the receiver detects a low SNR, but attempts to hold tracking until the SNR improves.

These phases are indicated by a mode number: 0 through 5 indicates stages of the acquisition phase, 6 indicates tracking, and 7 and 8 indicates low SNR conditions. Signal strength and SNR obviously affect the tracking mode. Since a separate mode number is maintained for each transmitter, signal

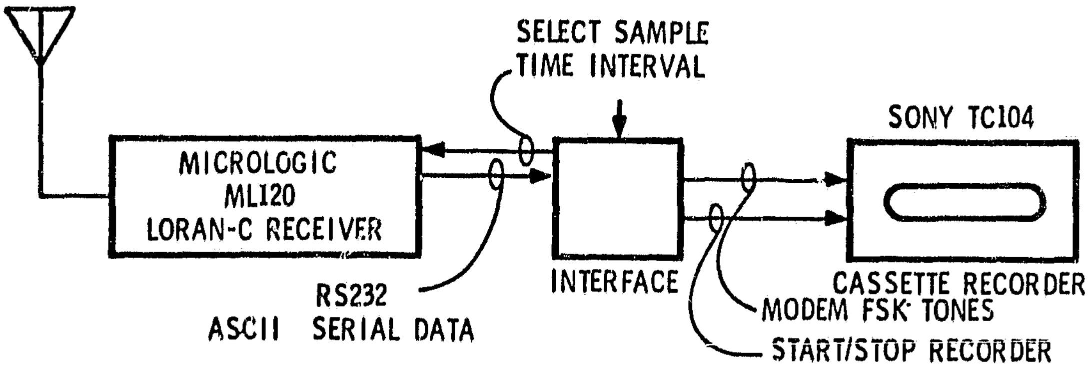


FIGURE 2.3-3. EQUIPMENT AT THE GROUND MONITOR SITES

availability can be related to tracking mode. However, the data-output software of the ML-120 uses the master signal to establish the clock that controls the data transfer. Therefore, if the master signal is lost, no data will be recorded, and all stations may appear unavailable.

As shown in Table 2.3-1, signal availability is also related to the blink indicator. The blink indicator is used to signal that the chain monitor has determined that an out-of-tolerance condition exists at a transmitter and it should therefore not be used for navigation. The blink signal is transmitted to the receiver by modulating the transmitter pulse.

Signal strength, noise, and interference are represented in the SNR number. The SNR number is a coded value ranging from 0 to 247 that can be related to the signal-to-noise ratio measured by the receiver. The calibration curve, shown in Figure 2.3-4, is taken from Reference 9. As described above, low SNR conditions also cause a change in mode number.

Propagation anomalies show up directly as variations in the measured TDs. Since the receiver is situated at a fixed location, receiver outputs should remain relatively constant. Any variations can be directly correlated with external physical phenomena. Unfortunately, problems with tracking due to envelope-to-cycle difference may also show up in the TDs as a cycle slip of approximately 10 microseconds, and these two effects must be separated.

The receiver also measures an envelope number. This number is used to control envelope tracking in the receiver during acquisition and can be linked to the ECD of the signal by the calibration curve of Figure 2.3-5, which is taken from Reference 9. However, a problem was found with the use of the envelope number as a measure of ECD. The envelope tracking gains are reduced when the receiver is tracking the phase of the signal. If then the ECD wanders away from the envelope number, it will take 2 to 3 minutes for the envelope number to follow. When this situation occurs the usefulness of the envelope number as a measure of true ECD in the test data is impaired.

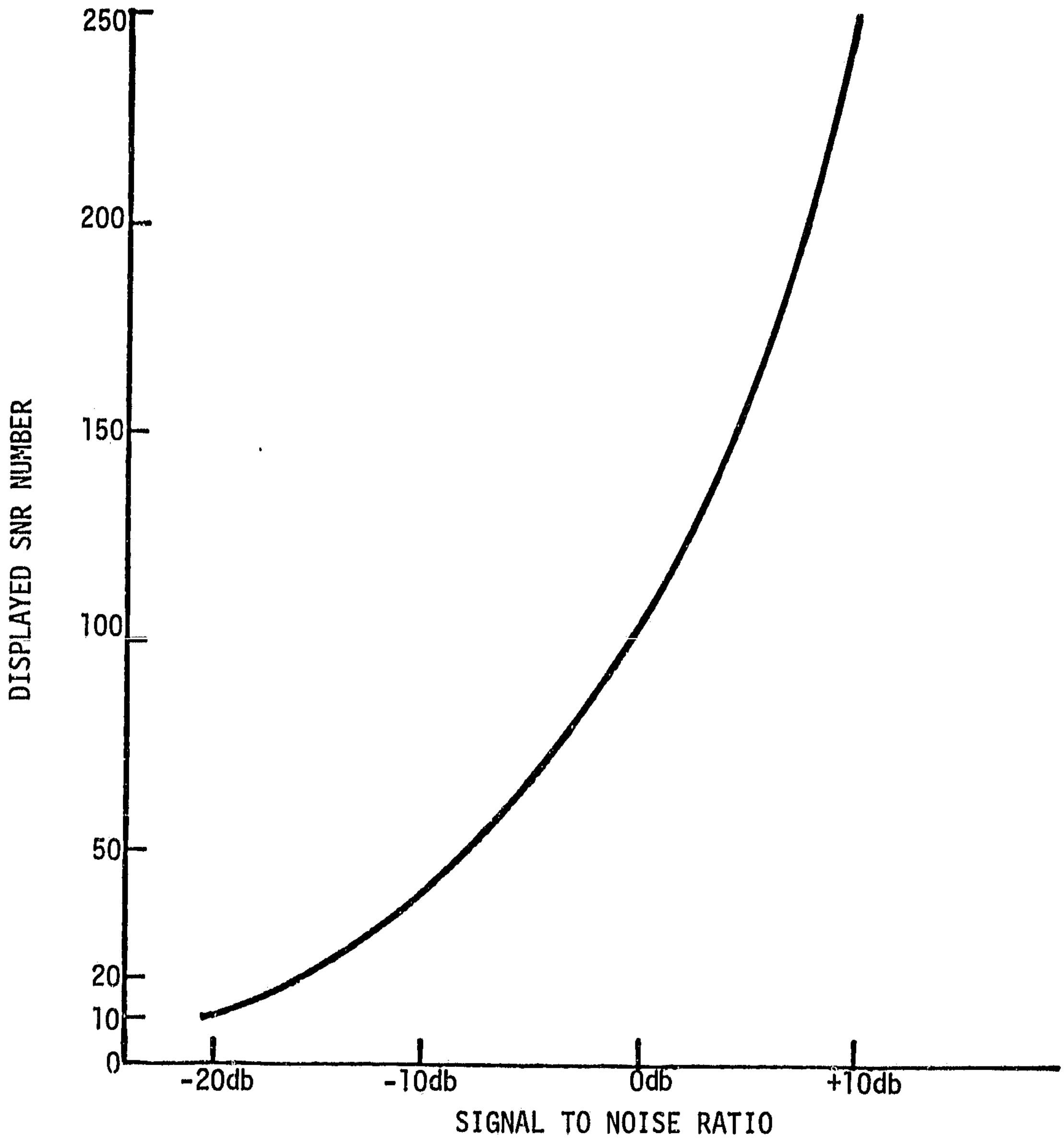


FIGURE 2.3-4. SIGNAL-TO-NOISE RATIO VS. SNR NUMBER DISPLAYED - MICROLOGIC ML 120 LORAN-C RECEIVER

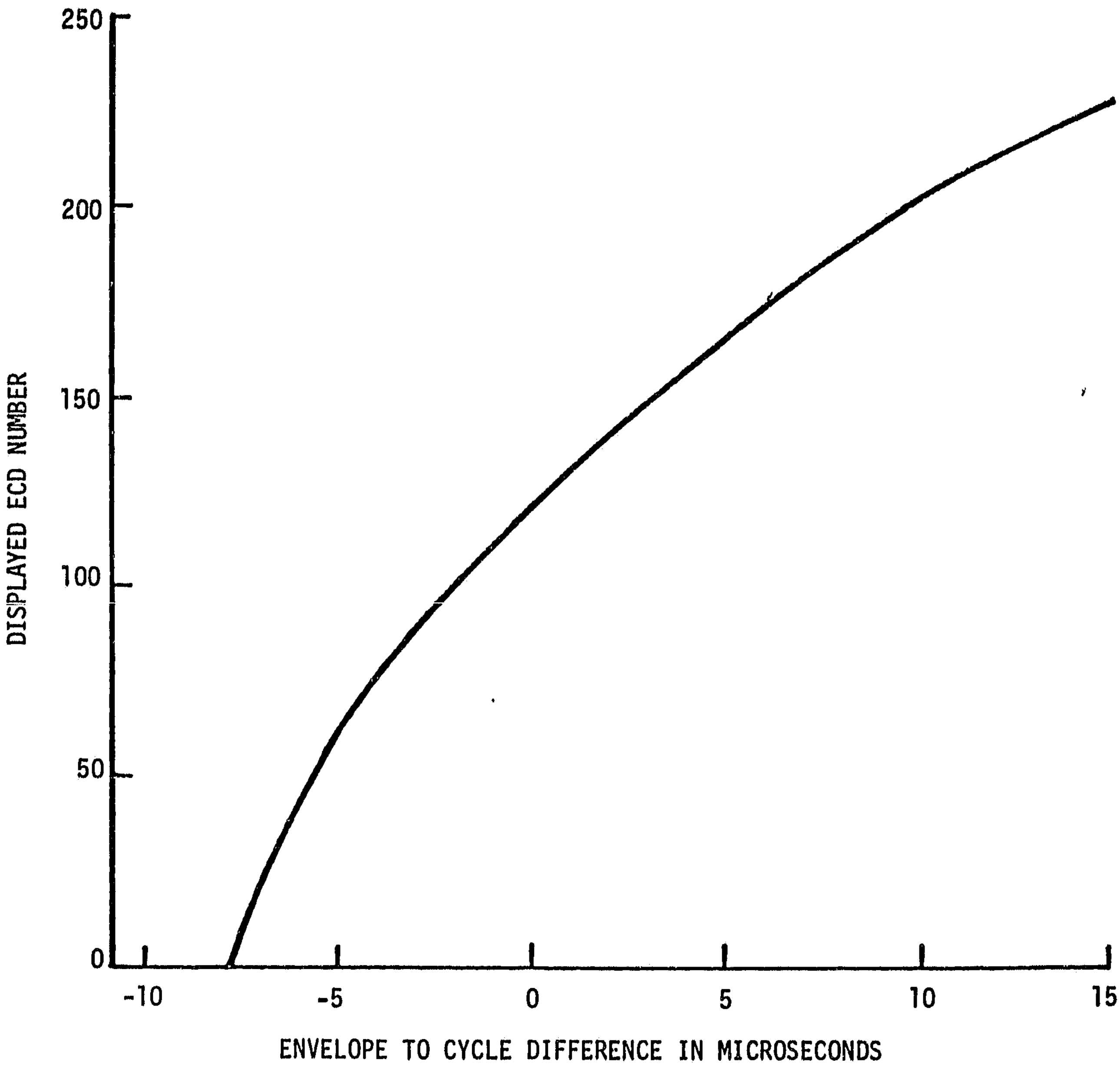


FIGURE 2.3-5. ENVELOPE-TO-CYCLE DIFFERENCE VS. ECD NUMBER DISPLAYED - MICROLOGIC ML 120 LORAN-C RECEIVER

2.3.3 Test Results and Conclusions

Data acquired from the ground-based units were analyzed in detail. It was concluded that LORAN-C reception in the Vermont airport EM environment can easily support uninterrupted operation while the aircraft is on the ground or at any altitude. The temporal stability (repeatability) of the data was found to be more than adequate to support operation within AC90-45A requirements. The availability of LORAN-C signals was assessed by a review of the Seneca station logs and found to be very high, consistent with Coast Guard objectives. Details of this analysis are presented below.

2.3.3.1 Signal Quality in an Airport Environment - A situation experienced at some airports is the presence of EM local interference which results in low SNR within the LORAN-C receiver. A SNR below -10db could prevent a receiver from establishing automatic signal tracking state before leaving the airport surface. A SNR below -15db could cause a receiver to lose track when operating in the vicinity of the airport. The ground monitor system data indicates that low SNR is not a problem in Vermont. Table 2.3-2 shows the number of points recorded at each SNR level for the period from 1 May 1980 to 1 September 1980. It will be seen that the transmitters in the primary triad (Seneca, Caribou, and Nantucket) provide very high SNRs. Carolina Beach provides an acceptable SNR most of the time, while Dana provides an unacceptable SNR a large percentage of the time, as expected (see Appendix A). Table 2.3-3 summarizes the percentages of data samples that yielded SNRs above the -10 db level required for initial signal acquisition.

Although problems with Micrologic stationary monitor equipment prevented acquisition of good data during the winter months, the TDL-711 monitor unit in the NASA trailer did provide coverage for the entire year. These data, as typified by Figures 2.3-6 through 8, confirmed the high SNRs of the primary triad.

Since a large ECD can cause cycle slip or false initial acquisition, an attempt was made to evaluate the ECDs of the transmitted LORAN-C signals. The envelope numbers recorded by the receivers were converted to microseconds using the calibration curve of Figure 2.3-5. Unusual distributions of

TABLE 2.3-2. DISTRIBUTION OF SNR NUMBERS RECORDED FROM 1 MAY 1980 TO 1 SEPTEMBER 1980

TRANSMITTER	RANGE OF VALUES		QUANTITY OBSERVED IN THIS RANGE (BY SITE)		
	LOWER LIMIT (db.)	UPPER LIMIT (db.)	BURLINGTON	NEWPORT	RUTLAND
SENECA	-30	-20	00	01	00
	-20	-18	00	00	00
	-18	-16	00	00	00
	-16	-14	00	00	00
	-14	-12	00	00	00
	-12	-10	00	00	00
	-10	-08	00	00	00
	-08	-06	00	00	00
	-06	-04	01	00	00
	-04	-02	00	00	00
	-02	+00	00	00	00
	+00	+10	2746	5199	3173
CARIBOU	-30	-20	00	05	05
	-20	-18	00	00	01
	-18	-16	00	00	02
	-16	-14	00	01	02
	-14	-12	00	00	01
	-12	-10	00	00	01
	-10	-08	00	00	03
	-08	-06	00	00	06
	-06	-04	00	00	13
	-04	-02	00	00	12
	-02	+00	01	00	11
	+00	+10	2746	5194	3116
NANTUCKET	-30	-20	00	08	01
	-20	-18	00	00	00
	-18	-16	00	00	00
	-16	-14	00	00	00
	-14	-12	00	00	00
	-12	-10	00	01	00
	-10	-08	01	01	00
	-08	-06	09	01	01
	-06	-04	05	00	01
	-04	-02	05	02	00
	-02	+00	18	03	00
	+00	+10	2707	5184	3169
CAROLINA BEACH	-30	-20	03	18	01
	-20	-18	03	21	00
	-18	-16	12	31	00
	-16	-14	24	103	01
	-14	-12	39	167	02
	-12	-10	58	228	03
	-10	-08	150	556	08
	-08	-06	256	459	12
	-06	-04	312	260	15
	-04	-02	295	209	44
	-02	+00	309	289	46
	+00	+10	1284	2858	3041
DANA	-30	-20	62	39	05
	-20	-18	61	61	04
	-18	-16	124	140	13
	-16	-14	210	235	17
	-14	-12	267	371	37
	-12	-10	276	354	48
	-10	-08	498	532	136
	-08	-06	392	304	169
	-06	-04	225	422	142
	-04	-02	143	836	168
	-02	+00	119	921	200
	+00	+10	370	985	2233

TABLE 2.3-3. PERCENTAGES OF SAMPLES WITH ACCEPTABLE SNR (GREATER THAN -10 db)

	MONITOR SITE		
TRANSMITTER	BURLINGTON	NEWPORT	RUTLAND
SENECA	100.0	100.0	100.0
CARIBOU	100.0	99.9	99.6
NANTUCKET	100.0	99.8	100.0
CAROLINA BEACH	94.9	89.1	99.8
DANA	63.6	76.9	96.1

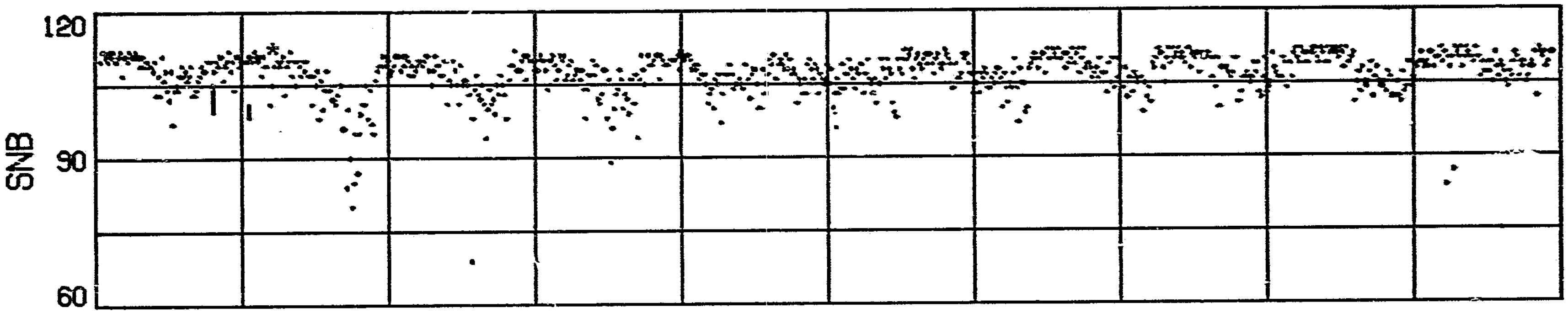


FIGURE 2.3-6. SNR TIME HISTORY FOR NANTUCKET AT BURLINGTON (13 NOV 79 TO 28 NOV 79)

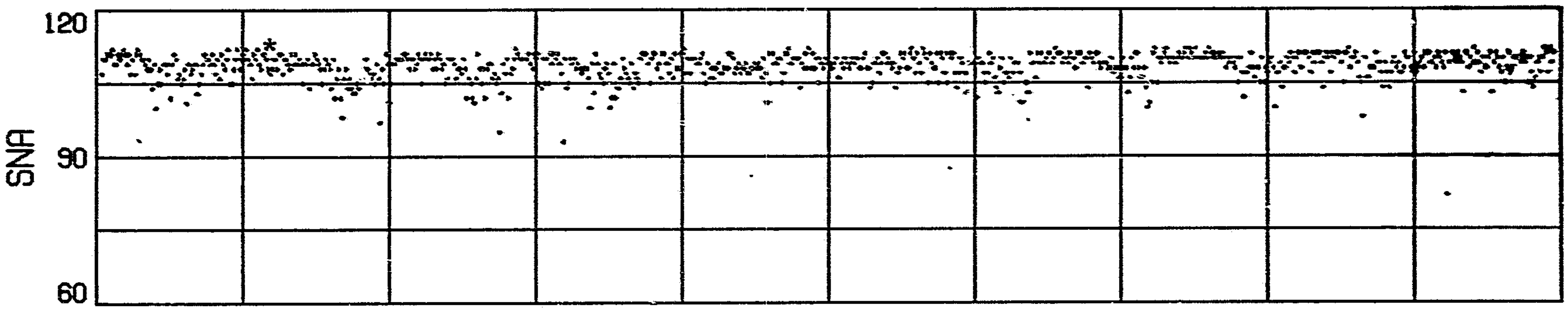


FIGURE 2.3-7. SNR TIME HISTORY FOR CARIBOU AT BURLINGTON (13 NOV 79 TO 28 NOV 79)

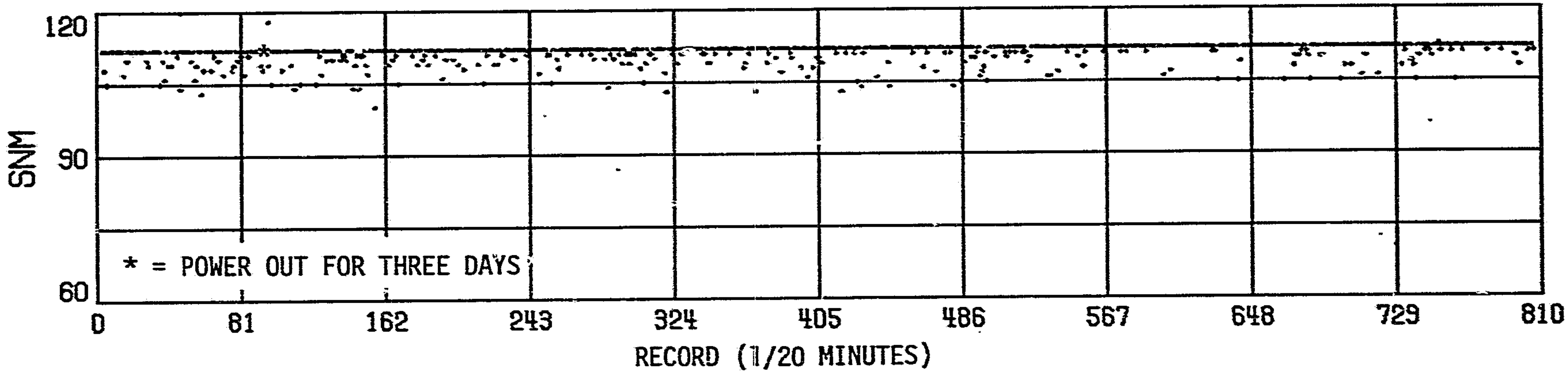


FIGURE 2.3-8. SNR TIME HISTORY FOR SENECA AT BURLINGTON (13 NOV 79 TO 28 NOV 79)

envelope numbers were noted, as shown in Table 2.3-4. The ECDs were also checked indirectly by examining distributions of the TDs recorded at the monitors, and only a small percentage of cycle slips were noted. Therefore, it is considered unlikely that major problems with the ECD actually occurred. In view of this hypothesis and because of the receiver characteristics discussed in the previous section, it was concluded that the envelope numbers recorded during the ground monitor tests could not be used as an accurate measure of ECDs.

2.3.3.2 Temporal Stability of Time Differences - Temporal variations were resolved into seasonal and diurnal subsets. Seasonal variations were investigated by first averaging all the data gathered within a given day then comparing the result as a variance from a nominal TD value. Figures 2.3-9 and 10 illustrate long-term seasonal results, variances by Julian Day for Caribou (Nominal TD 14227.6 microseconds) and Nantucket (Nominal TD 27269.5 microseconds) respectively. Each point represents the daily average of TD data. A blank space indicates that no data was available for that day. Although problems with the monitor equipment did not permit acquisition of continuous data, a definite seasonal variation of 0.5 microseconds peak-to-peak could be seen which translates to change in position, peak-to-peak, of the order of 360 feet. This variation is also evident in the data collected in the trailer at Burlington, Figures 2.3-11 and 12. Such a variation is to be expected as a result of seasonal changes in ground conductivity.

Although only a relatively small seasonal effect was observed, this data should be interpreted with some caution, since Vermont experienced somewhat unusual weather during the winter of 1979-1980. The unusually low snowfall may have produced a smaller than normal change in surface conductivity. Nonetheless, there is such a large error margin between observed TD variations in Vermont and AC90-45A requirements that even with significant climatological changes there should be no difficulty in meeting accuracy requirements even without use of calibration procedures.

TABLE 2.3-4. DISTRIBUTION OF ENVELOPE NUMBERS RECORDED FROM 1 MAY 1980 TO 1 SEPTEMBER 1980

TRANSMITTER	RANGE OF VALUES		QUANTITY OBSERVED IN THIS RANGE (BY SITE)		
	LOWER LIMIT (μ sec.)	UPPER LIMIT (μ sec.)	BURLINGTON	NEWPORT	RUTLAND
SENECA	-08	-05	00	00	33
	-05	-04	00	00	119
	-04	-03	00	00	106
	-03	-02	00	00	70
	-02	-01	00	00	29
	-01	+00	01	32	02
	+00	+01	42	1158	04
	+01	+02	438	3305	06
	+02	+03	1839	700	42
	+03	+04	411	04	203
	+04	+05	13	00	1666
	+05	+10	00	00	894
	+10	+15	00	00	00
CARIBOU	-08	-05	00	01	90
	-05	-04	00	00	26
	-04	-03	00	00	24
	-03	-02	00	04	79
	-02	-01	00	03	222
	-01	+00	13	1098	234
	+00	+01	84	3840	104
	+01	+02	356	245	65
	+02	+03	1289	07	27
	+03	+04	866	00	20
	+04	+05	133	00	40
	+05	+10	03	00	1259
	+10	+15	00	01	982
NANTUCKET	-08	-05	00	04	18
	-05	-04	02	00	32
	-04	-03	14	00	97
	-03	-02	30	00	152
	-02	-01	11	00	101
	-01	+00	12	05	14
	+00	+01	02	285	03
	+01	+02	07	2027	04
	+02	+03	32	2579	10
	+03	+04	159	285	88
	+04	+05	1092	11	373
	+05	+10	1382	01	2276
	+10	+15	00	00	04
CAROLINA BEACH	-08	-05	00	08	55
	-05	-04	03	16	26
	-04	-03	21	48	66
	-03	-02	43	103	118
	-02	-01	64	169	132
	-01	+00	62	375	91
	+00	+01	88	394	60
	+01	+02	166	734	58
	+02	+03	371	1169	03
	+03	+04	616	1171	117
	+04	+05	735	729	196
	+05	+10	676	283	1852
	+10	+15	00	00	338
DANA	-08	-05	01	10	61
	-05	-04	01	14	20
	-04	-03	92	69	61
	-03	-02	237	157	144
	-02	-01	347	281	400
	-01	+00	308	533	429
	+00	+01	182	754	224
	+01	+02	164	911	160
	+02	+03	190	1042	136
	+03	+04	225	801	109
	+04	+05	316	453	138
	+05	+10	678	172	929
	+10	+15	04	00	360

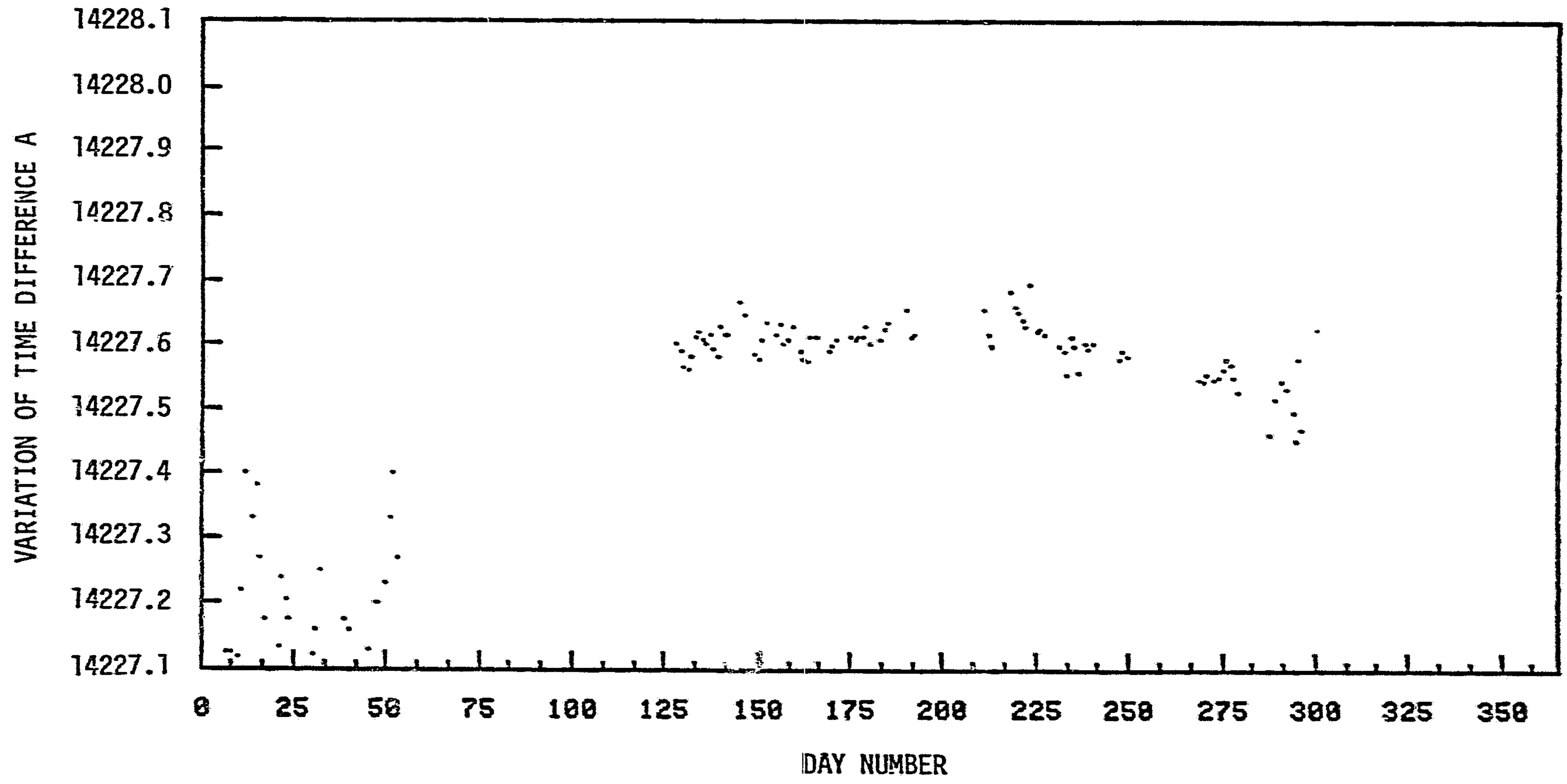


FIGURE 2.3-9. SEASONAL TD VARIATIONS FOR CARIBOU (ML-120) AT BURLINGTON

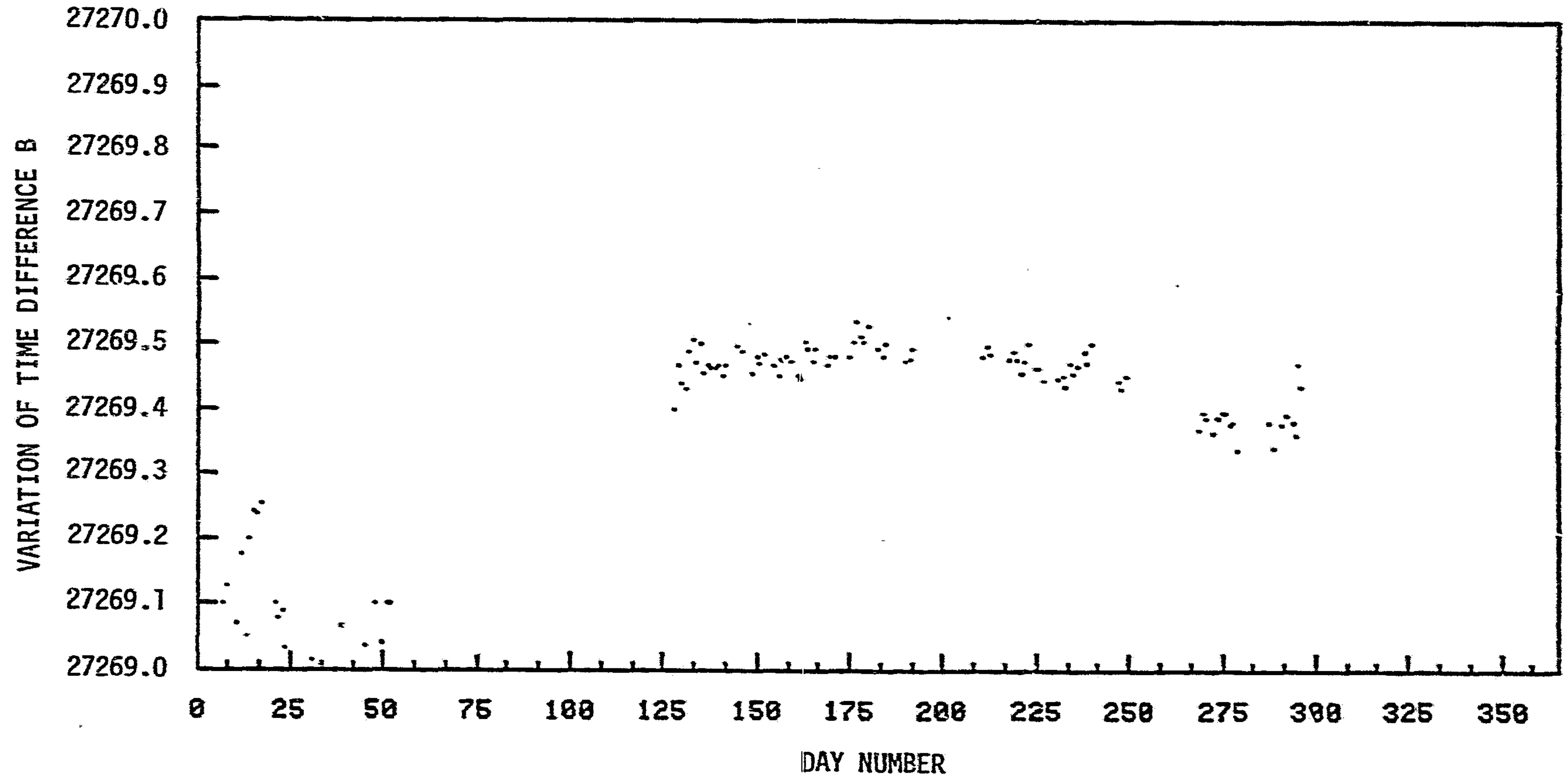


FIGURE 2.3-10. SEASONAL TD VARIATIONS FOR NANTUCKET (ML-120) AT BURLINGTON

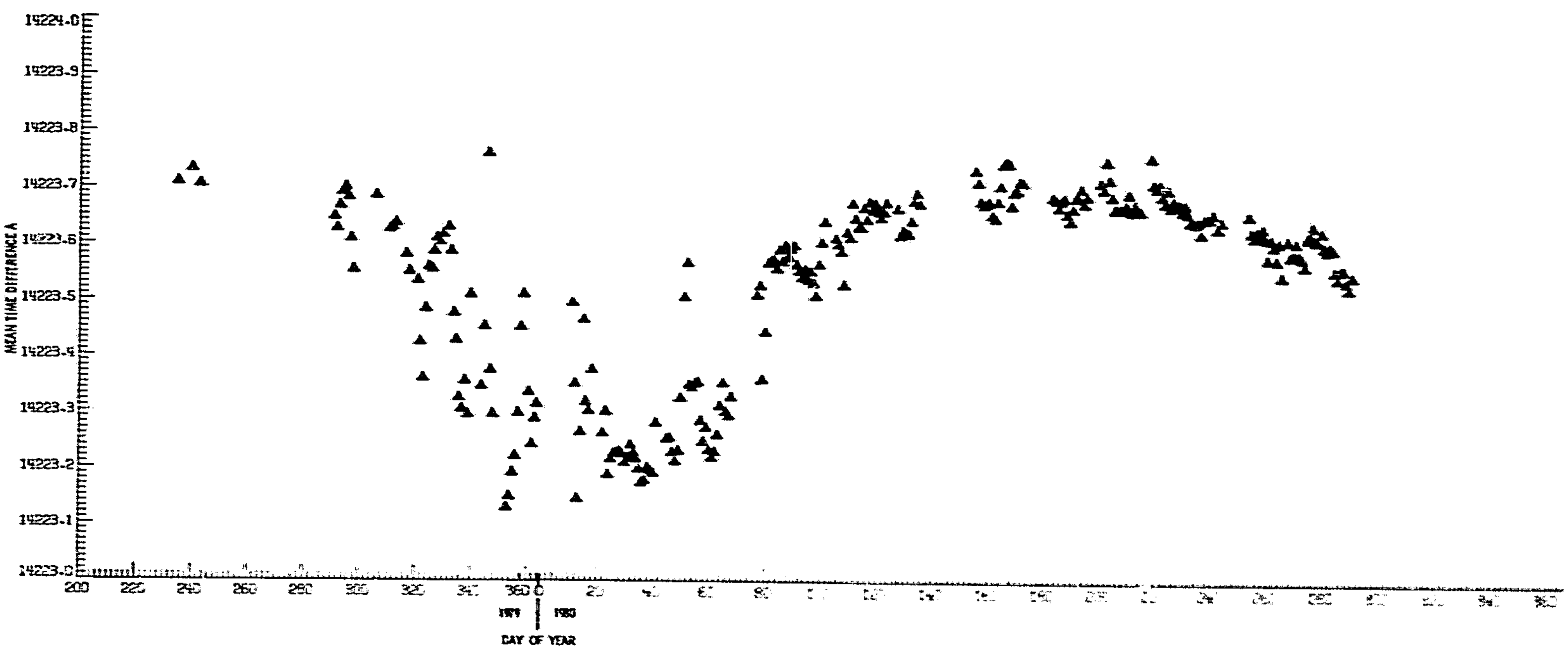


FIGURE 2.3-11. SEASONAL TD VARIATIONS FOR CARIBOU (TDL-711) AT BURLINGTON

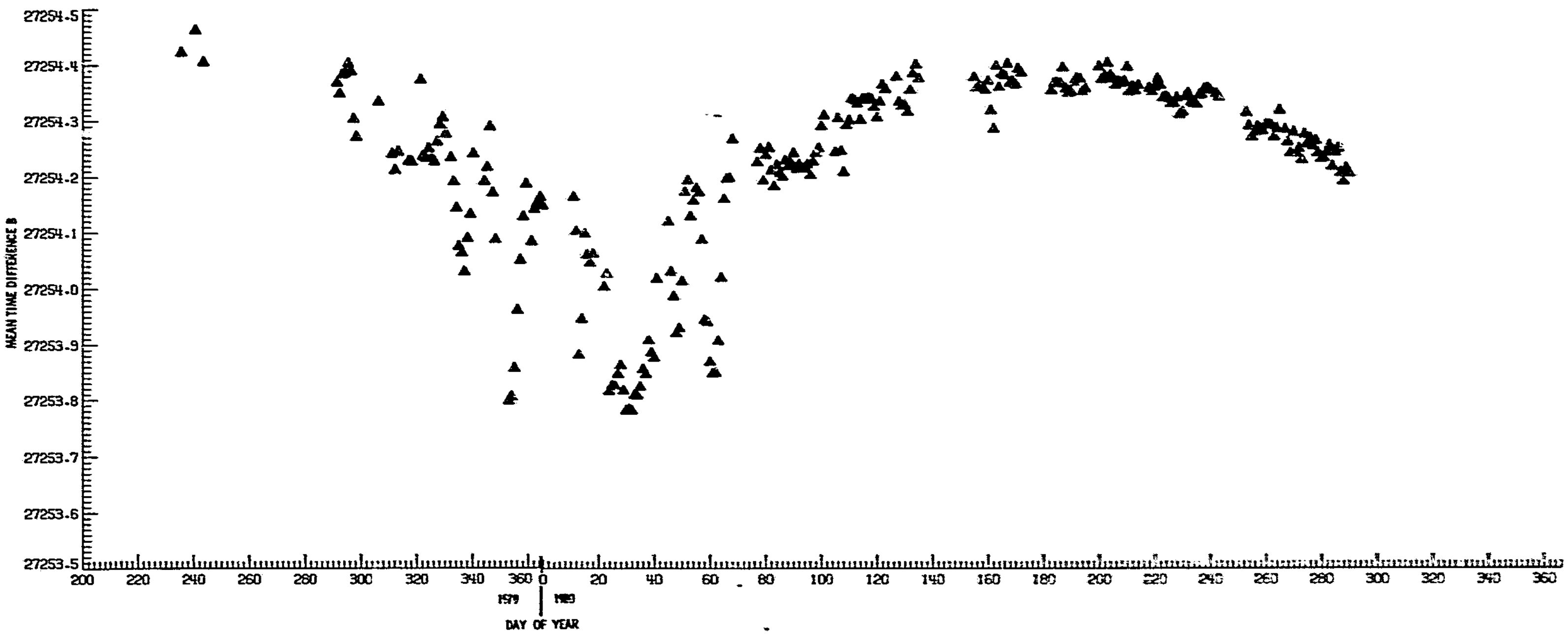


FIGURE 2.3-12. SEASONAL TD VARIATIONS FOR NANTUCKET (TDL-711) AT BURLINGTON

Diurnal TD variations were studied by taking averages of ground data for the same hour of the day, each day of collection. Typical diurnal averages for the 1 May 1980 through 1 September 1980 time period are shown in Figures 2.3-13 and 14. The figures also show the one-sigma limits derived from the sample variance. The variation in TDs is shown to be small over the day, typically less than 0.2 microseconds.

Similar averages were also formed from the trailer data. Figures 2.3-15 and 16 show the TD averages at Burlington. Although this data exhibits a larger dispersion (0.17 microsecond one-sigma), the mean variations are still quite small.

The total effect of all propagation anomalies on position error can be seen in Figure 2.3-17. Here the average position errors for the trailer data samples are plotted in north and east coordinates. Each data sampling period ranged from a few hours to several days. These data are referenced to true latitude and longitude, and therefore show the effects of grid bias as well as temporal propagation anomalies. The circle containing more than 98 percent of the observed data is also shown in the figure. Since the radius of this circle is only 0.06 nm, the observed data meets the AC90-45A 2 drms approach requirement of 0.45nm with a large margin to spare.

2.3.3.3 Signal Availability - The Coast Guard has established a goal of 99.7 percent availability for each LORAN-C station tabulated monthly. Table 2.3-5 shows the availability percentages computed from the Northeast U.S. chain logs from the period 3 December 1979 through 15 October 1980. A signal is defined as available if it is within Coast Guard tolerance and the transmitter is not blinking. Momentary outages of less than one minute do not count against availability, but authorized (scheduled) outages are counted.

All stations show availability levels above the Coast Guard goal, except for the master. However, this is somewhat misleading since current practice is to blink the master when a secondary is out of tolerance. Thus, the actual availability of the master is somewhat higher than shown in Table 2.3-5. In any case, the availability is significantly greater than 99 percent for the entire chain.

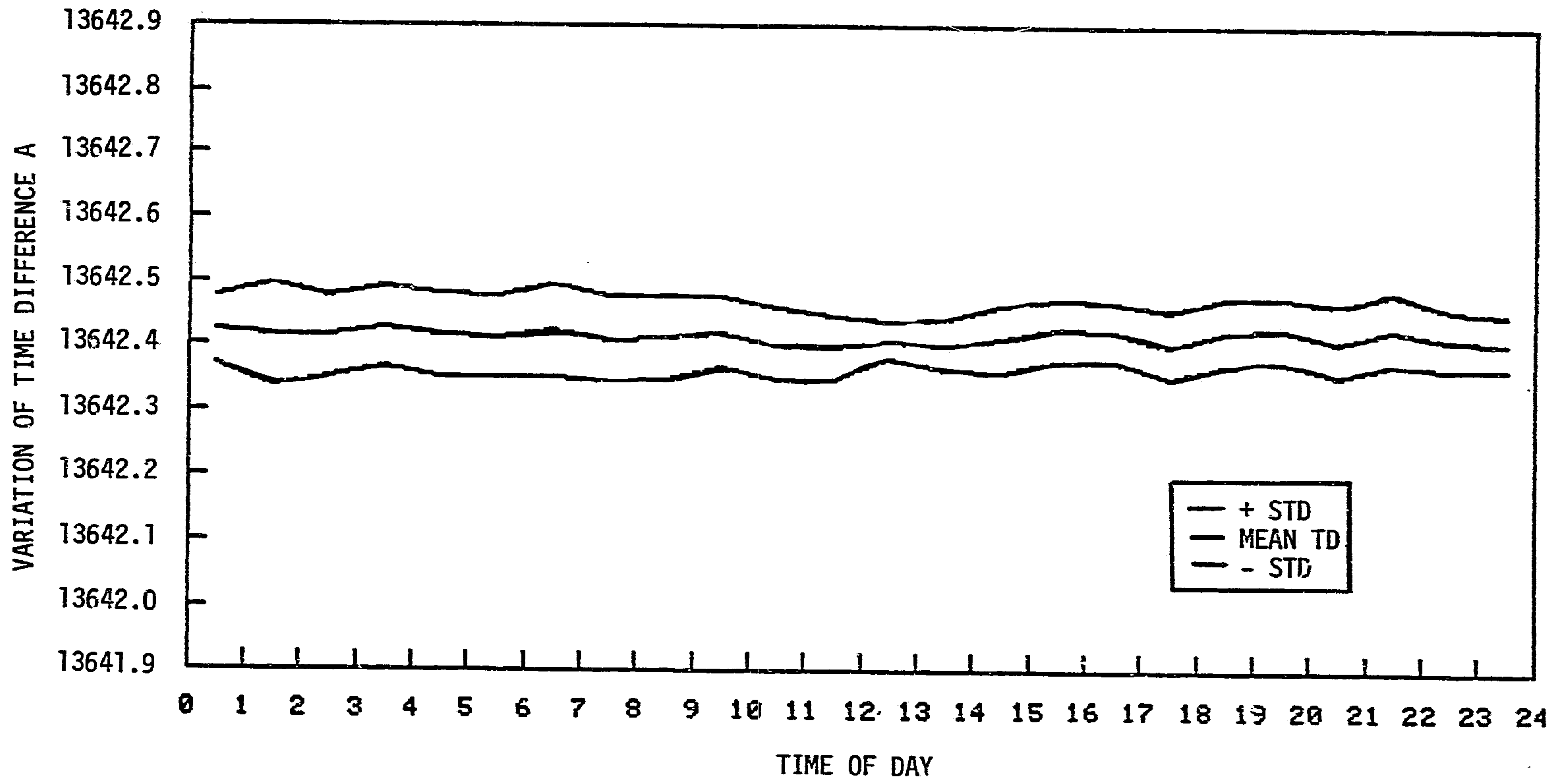


FIGURE 2.3-13. DIURNAL TD VARIATIONS FOR CARIBOU (ML-120) AT NEWPORT

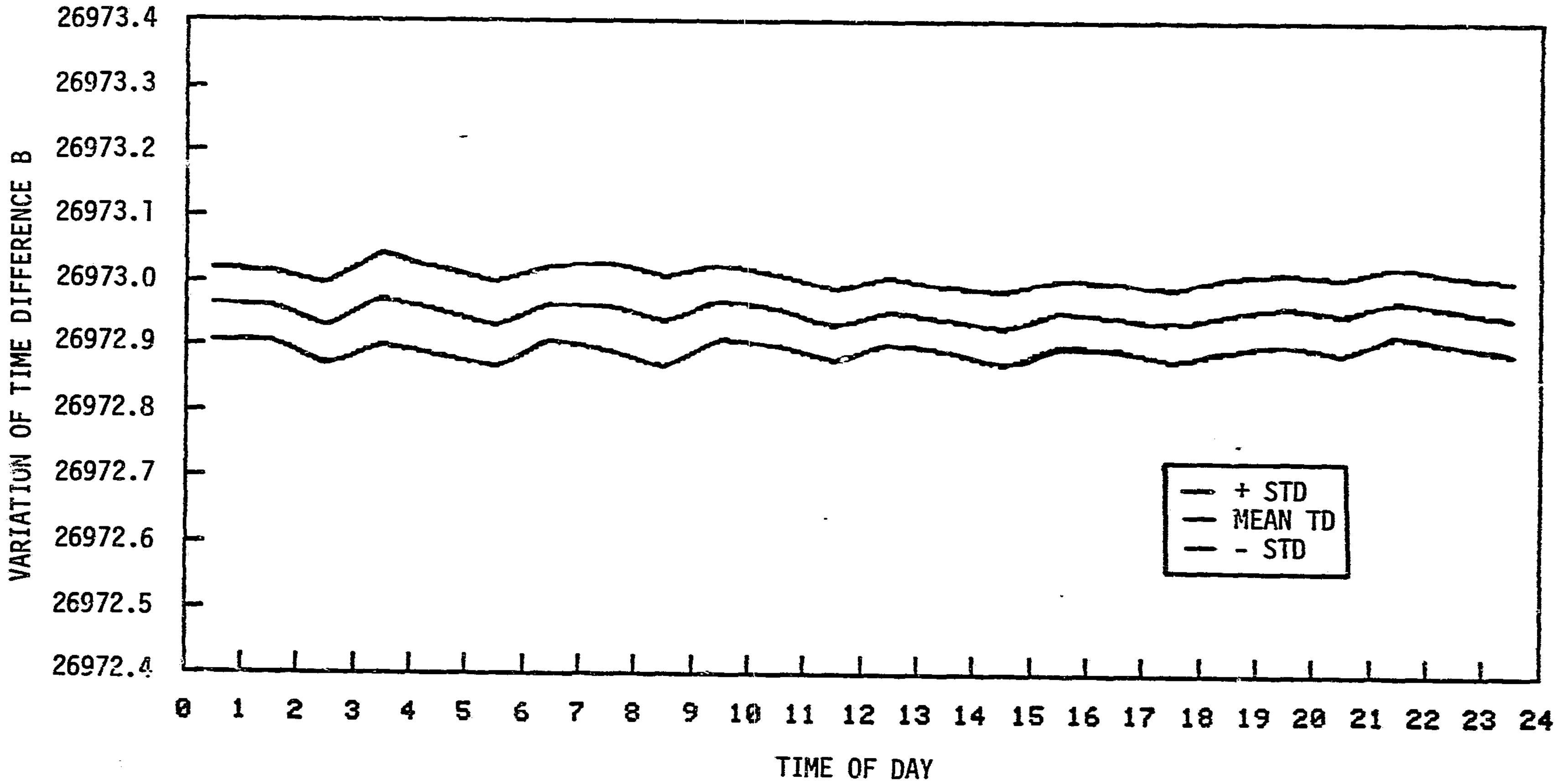


FIGURE 2.3-14. DIURNAL TD VARIATIONS FOR NANTUCKET (ML-120) AT NEWPORT

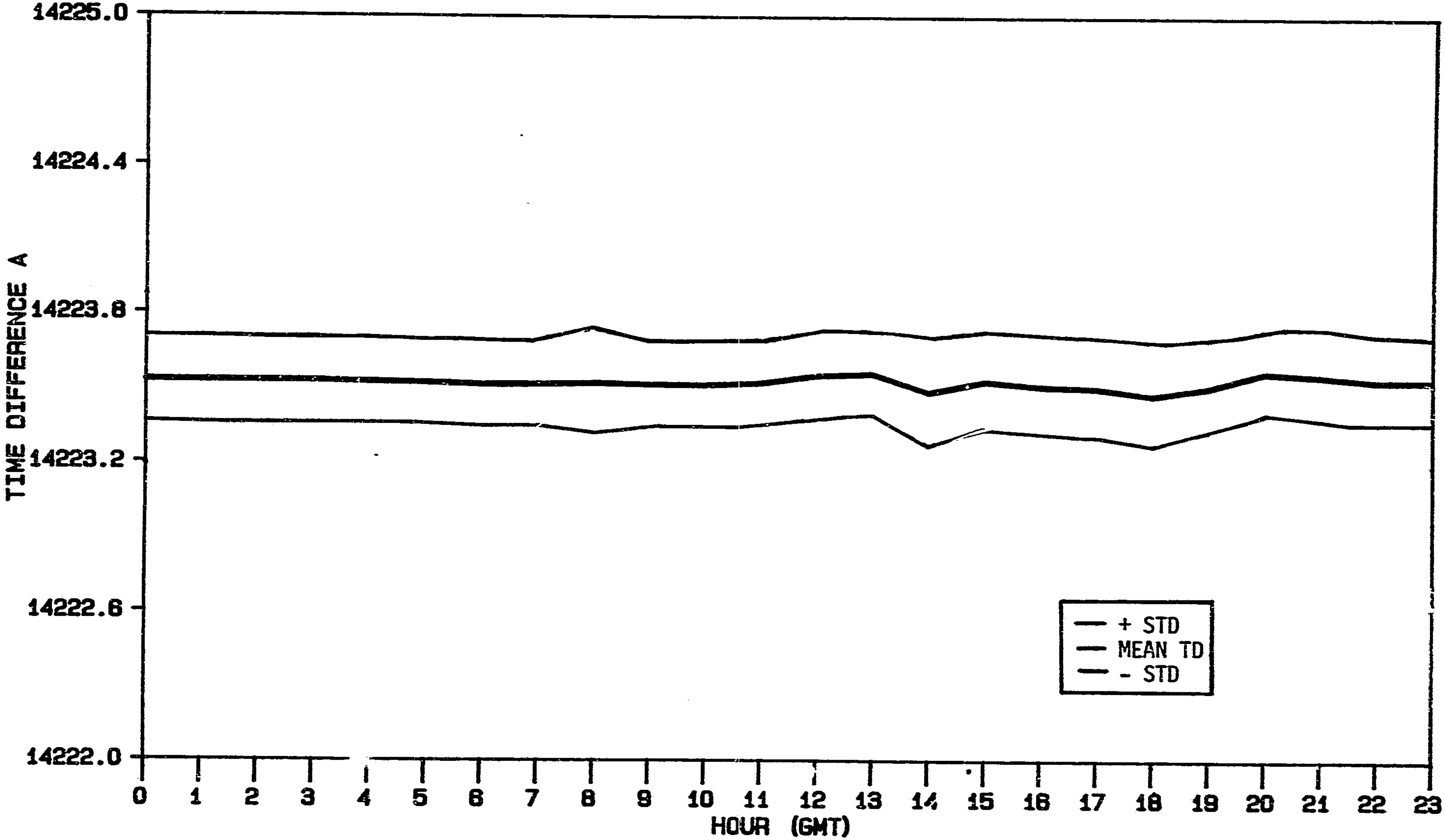


FIGURE 2.3-15. DIURNAL TD VARIATIONS FOR CARIBOU (TDL-711) AT BURLINGTON

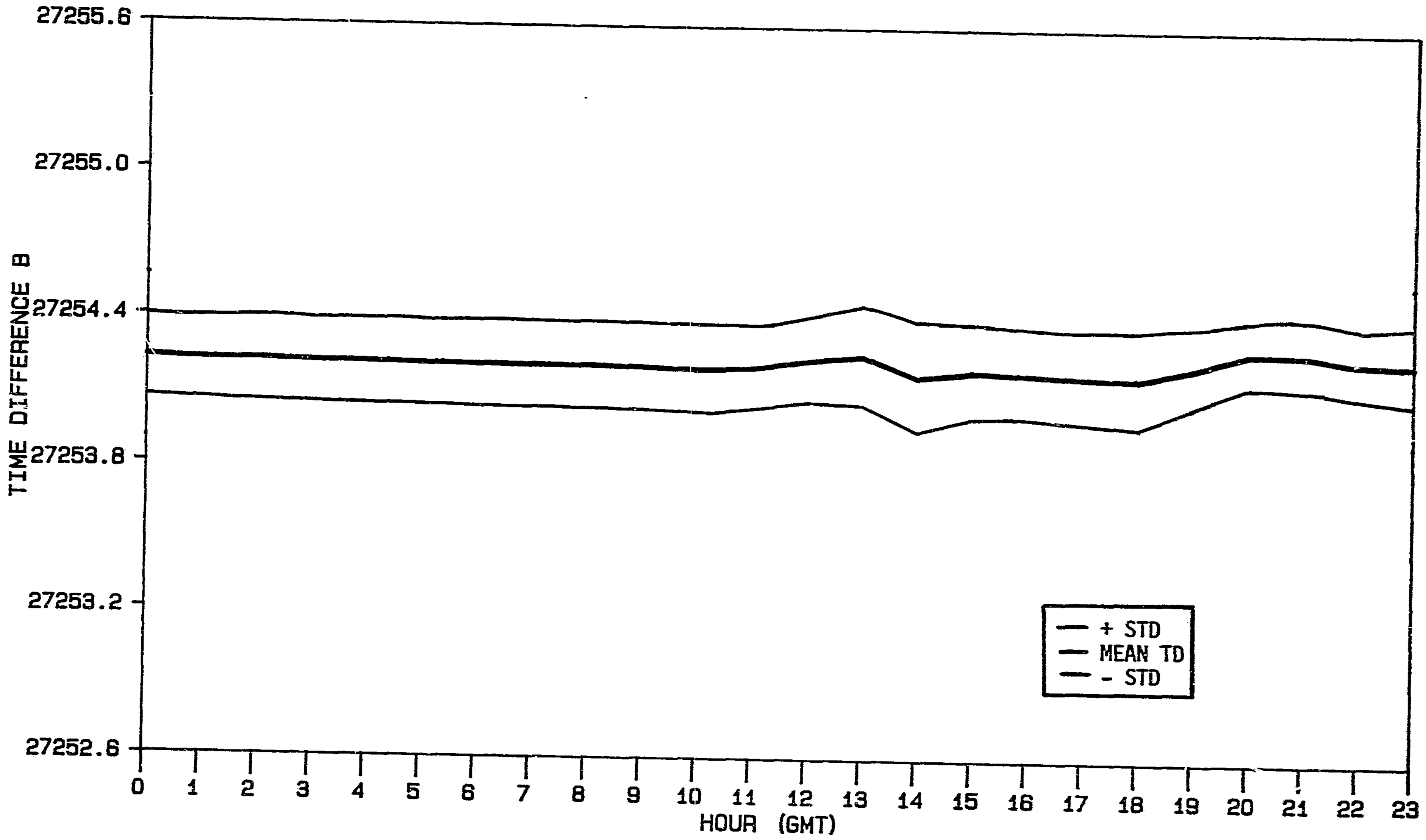


FIGURE 2.3-16. DIURNAL TD VARIATIONS FOR NANTUCKET (TDL-711) AT BURLINGTON

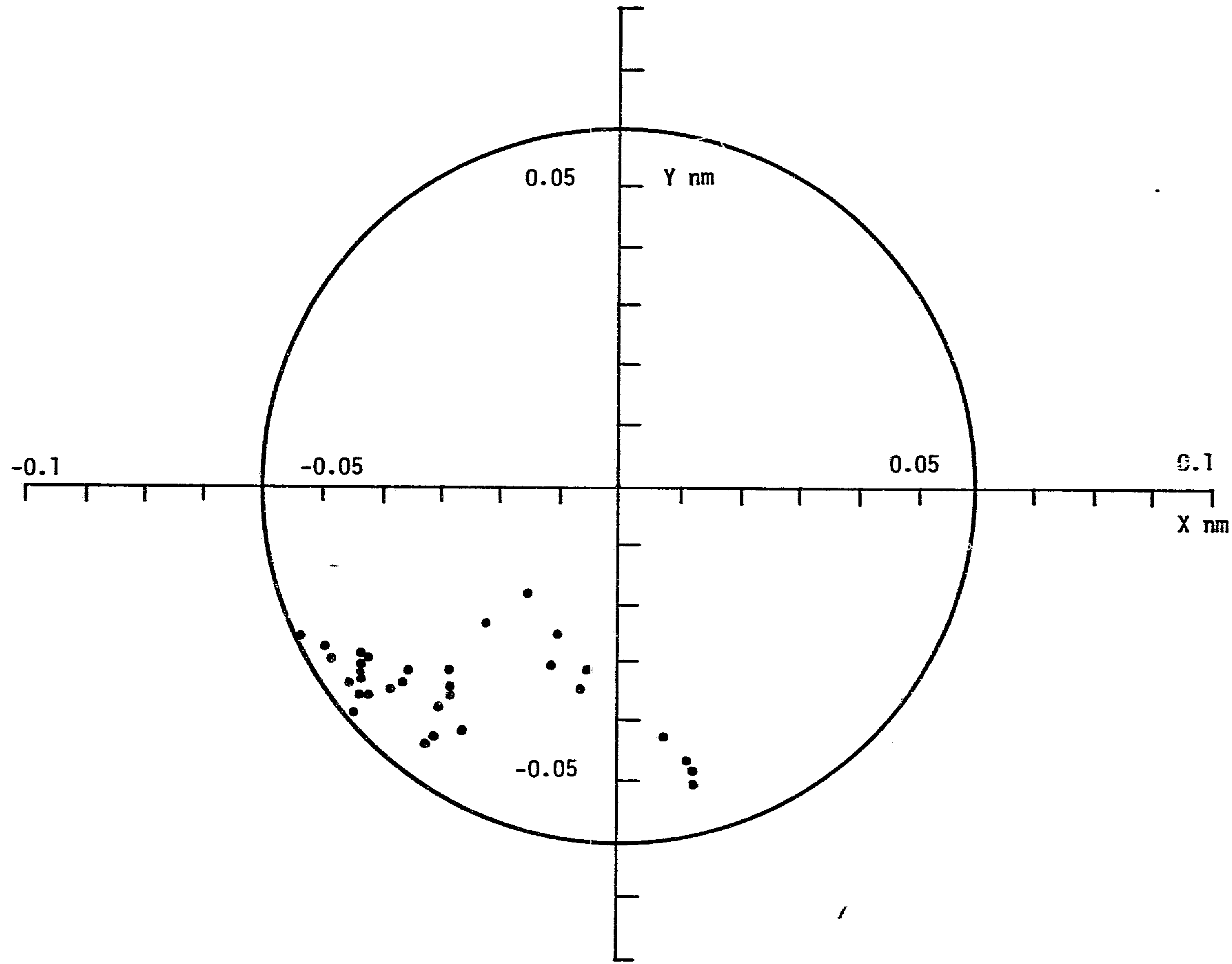


FIGURE 2.3-17. POSITION ERRORS FOR NASA/LRC DATA

TABLE 2.3-5. SIGNAL AVAILABILITY FOR THE NORTHEAST U.S. CHAIN (3 DECEMBER 1979 THROUGH 15 OCTOBER 1980)

TRANSMITTER	LOCATION	AVAILABILITY
MASTER	SENECA	99.61%
W SECONDARY	CARIBOU	99.94%
X SECONDARY	NANTUCKET	99.88%
Y SECONDARY	CAROLINA BEACH	99.75%
Z SECONDARY	DANA	99.91%

3. SUMMARY

3.1 PURPOSE

The principal goal of this test program was to generate a comprehensive data base of technical and operational experience with the LORAN-C navigator as an air navigation system. The specific objectives of the program were:

1. Document the achievable accuracy of the LORAN-C navigator as an RNAV system, for enroute, terminal and for non-precision approaches to remote airports in or near the mountainous terrain of Vermont.

2. Evaluate the operational and procedural requirements for routine use of the navigator in this environment.

3. Determine if the LORAN-C signal characteristics are compatible with the noise environment in Vermont, repeatable over long periods of time and available throughout the five airport test range.

4. Obtain FAA approval by Supplemental Type Certification (STC) for the LORAN-C equipment installation in the E50 Twin Bonanza permitting LORAN-C enroute navigation throughout the state.

The test program was designed to determine, the suitability of using a general aviation class, off-the-shelf, LORAN-C navigator as a means of navigating during enroute, terminal and non-precision approach operations. Minimum accuracy criteria established for the evaluation program are those specified by FAA Advisory Circular 90-45A "Approval of Area Navigation System for Use in the U.S. National Airspace System."

The goal was met and three specific objectives accomplished. The fourth objective, the awarding of the STC is in its final approval cycle.

3.2 SCOPE

Between mid-July 1979 and mid-October 1980, the Beech E50 completed 104 flights, totalling 226 hours of LORAN-C data acquisition. Each flight was designed to acquire both accuracy and pilot procedural data. During this time period four ground-based monitor units acquired extensive data describing the LORAN-C signal characteristics. Ground data and flight data were recorded simultaniously to permit temporal variations to be correlated. For reference data U.S. Coast Guard chain logs were obtained for the period of the test.

3.3 CONCLUSIONS

The LORAN-C system performance exceeded the accuracy requirements in AC90-45A for all phases of flight, during the entire test period without the use of calibration factors using the primary triad. Use of the LORAN-C system has operational benefits to the Air Traffic Control system and economical benefits to the general aviation user. The LORAN-C signal characteristics are compatible with the electromagnetic environment in Vermont. Temporal variations do not warrant using compensation values in the TDL-711 (none were used); and the signal was available for navigation in excess of 99 percent of the time.

Specific conclusions include:

1. LORAN-C RNAV can meet Vermont's need for a navigation aid capable of supplying accurate position and guidance information from ground level to any operating altitude and throughout the mountainous terrain characteristic of that state.

2. The system can be used effectively in conjunction with conventional FAA NAVAIDS for all phases of operations including departure, enroute, terminal area and non-precision approaches; thereby enhancing the utility of air transportation and significantly increasing pilot confidence under conditions of bad weather.

3. Sufficient accuracy and redundancy of LORAN-C transmitters exists from the Northeast chain to permit stand-alone LORAN-C RNAV operations in Vermont without compromising the safety and efficiency of the National Air Space System.

4. The operation of the Teledyne Systems Company TDL-711 RNAV system does not impose undue workload on the pilot, although there must be assurance of completion of appropriate training and familiarization just as with any other ARINC-class RNAV systems (e.g.,inertial, Doppler or Omega systems).

5. Airborne system reliability during more than 600 hours of inflight operation of the RNAV equipment exceeded 99 percent, determined by comparing the total time the system was operationally effective to total time the system was turned on.

6. The use of a calibration value for improving accuracy in a general area, particularly when using alternative triad configurations, and or use of a parallel offset input for local bias correction, are appropriate and effective operational procedures and can be accomplished without undue workload.

7. The use of LORAN-C RNAV in remote or mountainous regions like Vermont is fully compatible with the air traffic control system's requirements and procedures and, in fact, can be used to markedly reduce controller workload.

8. And finally, the data bases developed from airborne and ground test instrumentation provide a sample sufficiently large to permit the FAA to conduct limited certification of the Vermont E50 for enroute, terminal and approach operations using LORAN-C RNAV equipment.

APPENDIX A

LORAN-C PERFORMANCE CHARACTERISTICS

LORAN-C signals consist of pulse groups transmitted in rotation by the stations in a chain, as illustrated in Figure A-1. By measuring TDs between the times of arrival of the pulses generated by the master and secondary stations within a chain, hyperbolic LOPs are established. TD measurements from two stations pairs yield two LOPs whose intersection defines a position fix. General LORAN-C system characteristics are summarized in Table A-1.

To achieve high-resolution position fixes, a LORAN receiver must track not only individual pulse envelopes, but a particular radio frequency (RF) cycle within a pulse. The third cycle zero crossing (see Figure A-2) is generally used as the receiver tracking point: because it is the latest time in the pulse when the signal is sufficiently strong and is free of skywave signal interference. The third cycle is identified by the amplitude of the pulse envelope at the third zero crossing, which is nominally 63 percent of the pulse peak.

A-1 SIGNAL CHARACTERISTICS

The major characteristics of the LORAN-C signal relevent to air navigation are the signal coverage and the signal quality within the coverage area. These characteristics can be related to a number of critical performance parameters, as illustrated in Table A-2. These parameters represent the set of observable quantities which can be measured via ground monitoring to ensure that LORAN-C signal characteristics meet the requirements for air navigation.

A-1.1 Coverage

The authorized coverage area for each chain specified by the U.S. Coast Guard is a function of three system parameters. These parameters are: 1) signal-to-noise ratio (SNR) given in db, 2) LOP crossing angle (Ø) in degrees,

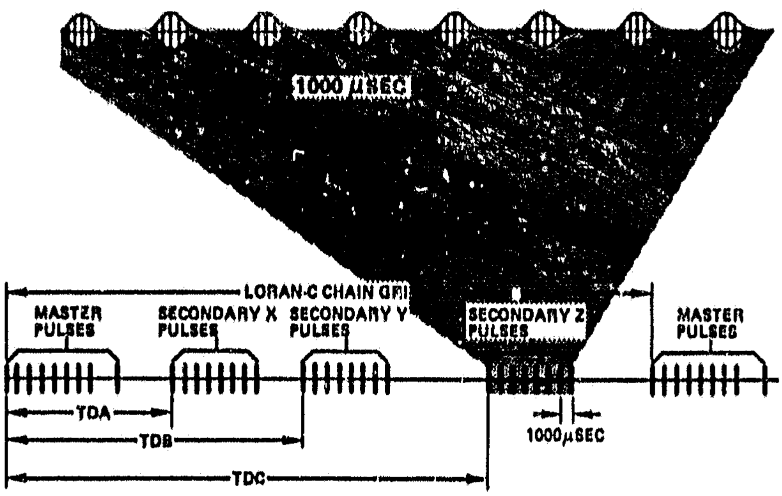


FIGURE A-1. LORAN-C PULSE GROUP

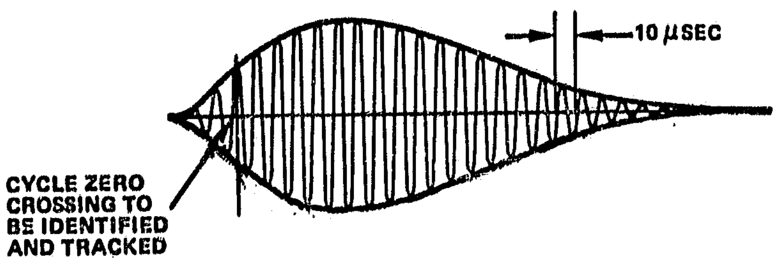


FIGURE A-2. LORAN-C PULSE

TABLE A-1. LORAN-C SYSTEM CHARACTERISTICS

Signal Characteristics	Pulsed, Hyperbolic 90 - 110 KHz
Accuracy - Predictable - Repeatable	 0.25 nm (2 drms)* 18 - 90 Metres (2 drms)*
Availability	> 99%
Coverage	Most of U.S.; Selected Overseas Areas
Fix Rate	> 10 Fixes/Second
Fix Dimension	2 or More LOPs
Capacity	Unlimited
Ambiguity	Theoretically yes, but easily resolved

*95% Probability.

TABLE A-2. LORAN-C PERFORMANCE PARAMETERS

CHARACTERISTIC	PARAMETERS	UNITS
COVERAGE	Signal - to - Noise Ratio (SNR) Signal Strength Lop Crossing Angle (ϕ) Signal Gradient (G) Availability	db db (1μv/m) degrees) ft./μsec %
SIGNAL QUALITY	Spatial Propagation Anomalies Multipath Anomalies Temporal Variations Atmospheric Anomalies Envelope - to - Cycle Discrepancy (ECD) In - Band Interference Cross - Chain Interference Skywave Contamination	μ sec. μ sec. μ sec. μ sec. μ sec. - - -

and 3) signal gradient (G), given in feet per microsecond. This last parameter, G, represents the divergence between the hyperbolic LOP's, being smallest along the baseline and becoming larger away from the baseline, approaching divergence near the baseline extensions.

The LORAN-C coverage area is defined by the following values of these parameters:

1. SNR > - 10 db
2. Ø > 30 degrees
3. G < 2000 feet per microsecond

While Ø and G are purely geometric parameters, SNR will vary, primarily due to variations in the noise environment. The dominant source of noise in the LF band is atmospheric noise, which is a function of geographic location, season, time of day, and weather conditions. From available data, a reasonable lower limit on the expected noise level is 45 db (1 microvolt/meter). To accomplish tracking at a minimum SNR of -10 db, a minimum field strength for the LORAN-C signal of 35 db (1 microvolt/meter) is therefore required.

The Northeast U.S. chain (GRI 9960) provides coverage for Vermont, as illustrated in Figure A-3. Table A-3 shows the location and transmitted power of each transmitter in this chain. Expected signal strengths in Vermont can be computed from transmitted power and distance using published attenuation curves (Reference 4). Table A-4 gives the range of signal strengths predicted at the Newport, VT data collection site for each station in the 9960 chain. The predictions are based on a likely variation of propagation path conductivities ranging from very low values for poor soil, snow or ice, to higher values for fresh water and good dry soil.

It can be seen from Table A-4 that Seneca, Caribou and Nantucket should provide a large margin of signal strength to maintain -10db SNR relative to 45 db atmospheric noise. Carolina Beach may provide adequate signal strength to act as a backup station, while Dana is somewhat marginal.

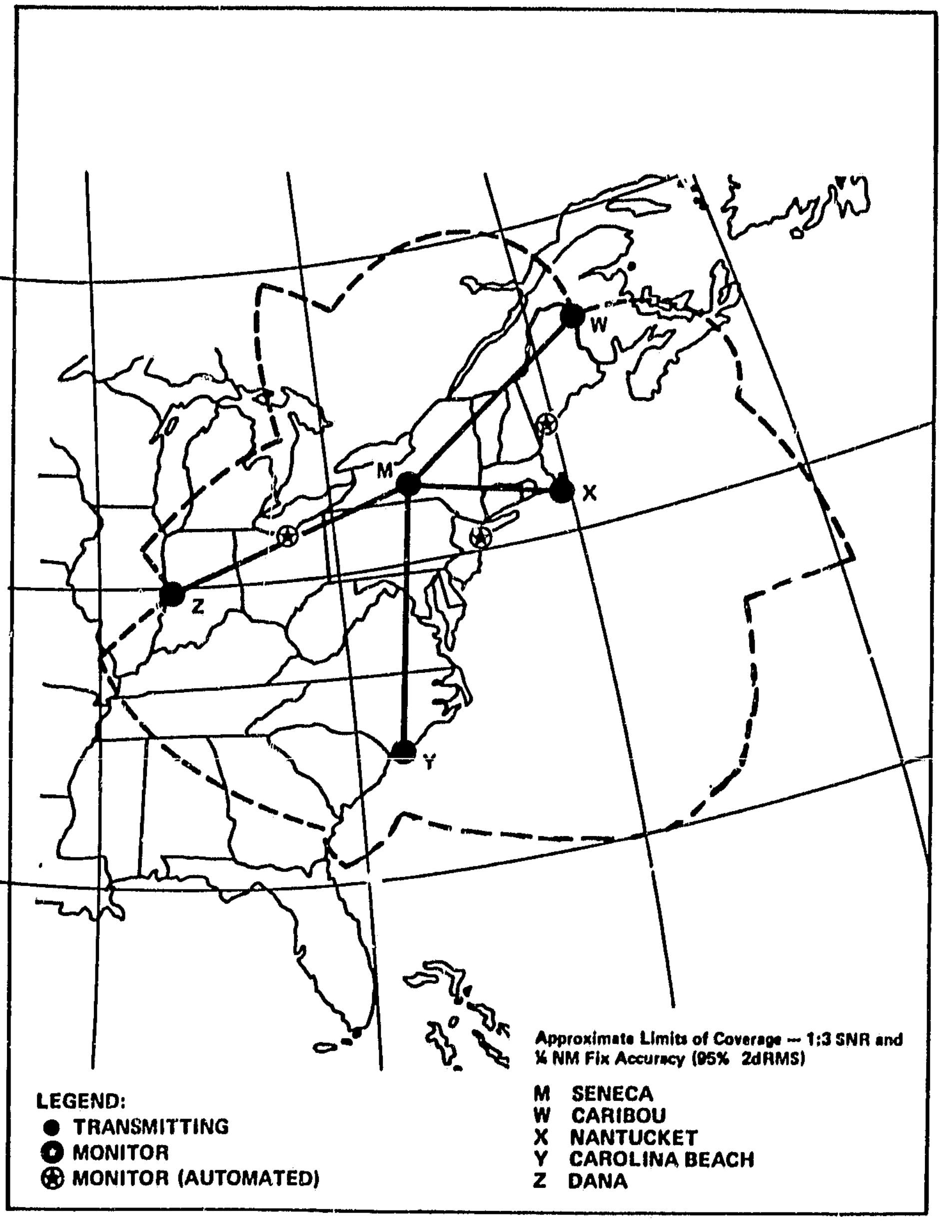


FIGURE A-3. NORTHEAST LORAN-C CHAIN CONFIGURATION

TABLE A-3. NORTHEAST U.S.A. LORAN-C CHAIN (GRI 9960)

STATION	COORDINATES	FUNCTION	CODING DELAY BASELINE LENGTH	RADIATED PEAK POWER
Seneca NY	42-42-50.60 N 76-49-33.06 W	Master	N/A	800 kw
Caribou ME	46-48-27.20 N 67-55-37.71 W	W Secondary	11,000 us 2797.20 us	350 kw
Nantucket MA	41-15-11.93 N 69-58-39.09 W	X Secondary	25,000 us 1969.93 us	275 kw
Carolina Beach NC	34-03-46.04 N 77-54-46.76 W	Y Secondary	39,000 us 3221.65 us	550 kw
Dana IND	39-51-07.54 N 87-29-12.14 W	Z Secondary	54,000 us 3162.06 us	400 kw

TABLE A-4. TYPICAL SIGNAL STRENGTHS COMPUTED FOR NEWPORT, VERMONT

TRANSMITTER	SIGNAL STRENGTH - db. ABOVE 1μv/m*
Seneca NY	69 - 75
Caribou ME	67 - 73
Nantucket MA	64 - 70
Carolina Beach NC	36 - 51
Dana IN	31** - 47

*Conductivity ranging from poor rocky soil to good dry soil.
**Minimum signal strength required is 35 db above 1μv/m Section A-1.

Table A-5 shows geometric parameters for the three Vermont Airport ground-test sites: Burlington, Newport and Rutland. A discussion of the ground-test configuration is given in Section 2.3.4. The table shows the gradient and bearing angle of the normal for each of the LOPs. Examination of this table shows that the gradients are all within adequate limits: they are less than the geometric limit of 2000 feet per microsecond. The crossing angle for a pair of LOPs is determined by differencing the bearing angles of the two normals. It can be seen that the Seneca-Caribou-Nantucket and Seneca-Caribou-Carolina Beach triads have adequate crossing angles (43 to 50 degrees) but the Seneca-Nantucket-Carolina Beach triad has a crossing angle less than 30 degrees at the two northern sites: Burlington and Newport. Therefore, this backup triad could be marginal in northern Vermont.

The total availability of LORAN-C depends on the availability of the primary and backup transmitter stations. The Coast Guard has established objectives for LORAN-C station availability (Reference 7). On a monthly basis, the objective is 99.7 percent for each station, which includes both scheduled and unscheduled outages. For purposes of supporting aviation requirements, a station will be assumed to be out of service during actual outages and during station blink, which is a special transmitted code used to identify that the signal is unusable. A station may be operating under blink conditions for any of the following reasons:

1. Operating at less than 50 percent of rated power
2. TD out of tolerance
3. ECD out of tolerance
4. Improper phase code or GRI

The above conditions are continuously monitored at the transmitters and at the SAMs. It is anticipated that the availability objective of 99.7 percent will be progressively easier to meet with the replacement of the old vacuum tube transmitting equipment with new solid state transmitters. However, it was noted that outages do occur, usually caused by power failures, tower maintenance, or antenna coupler failures, and such outages can affect operations over a wide area.

TABLE A-5. LOP PARAMETERS FOR MONITOR SITES

RECEIVER LOCATION	SECONDARY TRANSMITTER LOCATION	GRADIENT (ft/micro sec)	BEARING OF NORMAL (deg)
Burlington	Caribou	492	057
	Nantucket	668	100
	Carolina Beach	1559	129
Newport	Caribou	492	057
	Nantucket	739	107
	Carolina Beach	1667	131
Rutland	Caribou	509	060
	Nantucket	567	105
	Carolina Beach	1134	140

A-1.2 Signal Quality

The parameters which can be used as indicators of signal quality or listed in Table A-2. Four of these parameters are propagation anomalies which affect the accuracy of the TD's: spatial propagation anomalies, multipath, temporal (seasonal and diurnal) variations and atmospheric variations. Each of these effects is considered in the following paragraphs.

Spatial propagation anomalies are functions of ground conductivity along the path and the length of the path. Sea water has the highest conductivity values, fresh water and good dry soil paths have somewhat lower values. The lowest conductivity values, corresponding to the lowest propagation velocities are associated with poor soil, snow or ice, and urban areas. Spatial propagation anomalies result in a shift of the LORAN-C grid from its calculated position, based on a uniform conductivity model.

This grid shift will appear as a bias within a local region. As indicated in Section 2.1 the primary trial was used without a bias correction and exceeded all AC90-45A accuracy requirements. As discussed in the following Appendix, the minimum operational performance standards proposed for the low cost airborne LORAN-C receivers include provisions for such propagation anomaly corrections. It is assumed that such corrections will be either computed by the airborne receiving equipment or will be computed offline and supplied to the user equipment as precomputed offsets.

Multipath arises from signal reflections from mountains or large structures. These perturbations appear as extremely localized bulges in the LOP grid lines. In the case of buildings or other structures, these multipath effects may be less noticeable in the air than on the ground. Multipath could possibly be a problem in the vicinity of some airports, causing a position - fix error during the final stages of approach. There was no evidence of a multipath effect during any phase of flight at any of the airports used in the Vermont test program.

Temporal propagation variations result from seasonal and diurnal changes in ground conductivity and atmospheric conditions. Both seasonal and diurnal variations may have both area-wide and localized components. The SAMs, maintained by the Coast Guard, remove some of the area-wide temporal variations, because they monitor and control the TDs for their service areas. However, since the LORAN-C chain and SAMs are necessarily land based and the primary service areas are usually in coastal waters, there can be significant temporal variations of LORAN-C which would affect the airborne user. The corrections for localized variations in the vicinity of the SAMs did not deteriorate the navigation accuracy of the user in the State of Vermont.

The final propagation effect considered is that of atmospheric meteorological occurrences, predominantly frontal weather systems, which can introduce propagation anomalies in the affected paths. These effects tend to be localized rather than area-wide, and the magnitudes of these errors are usually small. Experience with the SAMs, however, has shown that such local weather variations can result in land phase adjustments which actually induce errors in other parts of the grid. The induced errors in Vermont were small because of good geometry.

Another signal quality parameter of interest is envelope-to-cycle difference (ECD). The LORAN-C pulse shape is monitored by the SAM and controlled at the transmitter to maintain a envelope amplitude of 63 percent of its peak value at the third-cycle zero crossing for a user in the primary service area. The ECD is defined as the time that the 63 percent amplitude point occurs on the envelope relative to the time of the third-cycle zero crossing.

A user in other than the primary service area will usually observe ECD. If the ECD becomes too large (greater than 5 microseconds) the receiver may slip a cycle and lock onto tne wrong zero crossing. This will cause a 10 microsecond error in measured TD resulting in a large position error, as large as 10,000 ft for the primary navigation triad in Vermont. Typically, the ECD will vary from a specified value of less than +2.5 microseconds in the vicinity of the transmitter to nearly zero in the primary service area. For the Northeast U.S. chain, the ECD values assigned at the SAM locations are

listed in the Table A-6. Variations at the SAMs of more than 1.5 microseconds from these nominal values will be flagged as abnormal. It is the goal of the USCG to control the ECDs to within ±2.5 microseconds over the entire coverage area to minimize the probability of cycle slip. A cycle slip will be detectable in the low cost airborne LORAN-C receivers.

Another possible source of problems with LORAN-C is in-band or adjacent-band interference. The U.S. Naval communication station at Annapolis, MD broadcasts at 88 kHz, just 2 kHz from the low end of the LORAN-C band. Figure A-4 is a spectrum photograph of the LF band recorded at Burlington, Vt during the Navy operation of its 88 kHz communication system. To prevent disruption of the LORAN-C signal, notch filtering is required to mask out this strong interfering source. A similar problem exists with respect to 115.3 kHz communication broadcasts from Nova Scotia. Fortunately, only a few such stations exist and appropriate notch filtering can adequately alleviate this interference problem.

In-band interference can also be troubling. Although there are no broadcast transmissions in the LORAN-C band within the U.S., power companies employ power line carrier (PLC) communications within the LF band to send control signals along high voltage transmission lines to outlying stations. Some of these transmissions fall within the LORAN-C bandwidth and can disrupt operation of LORAN-C in the immediate vicinity of these transmission lines, as discussed in Reference 8. At present, the only course of action is to avoid operations near any such interfering source. Fortunately, these effects should be quite small for aircraft at normal operating altitudes. The potential for increased interference by the promulgation of PLC communications by utilities should be considered, however, in assuming the adequacy of LORAN-C to support civil air navigation needs.

Another type of interference is cross-chain interference, which arises when pulses from one GRI periodically interfere with pulses from another GRI. This problem would be most severe when operating in the vicinity of a station which is dual-rated, i.e., one which operates as a member of two different

TABLE A-6. ASSIGNED ECDs FOR THE NORTHEAST U.S. CHAIN

STATION	ASSIGNED ECD AT SAM (micro sec)
Seneca	+1.6
Caribou	+1.8
Nantucket	+0.2
Carolina Beach	+1.5
Dana	+1.6
Tolerance ±1.5	

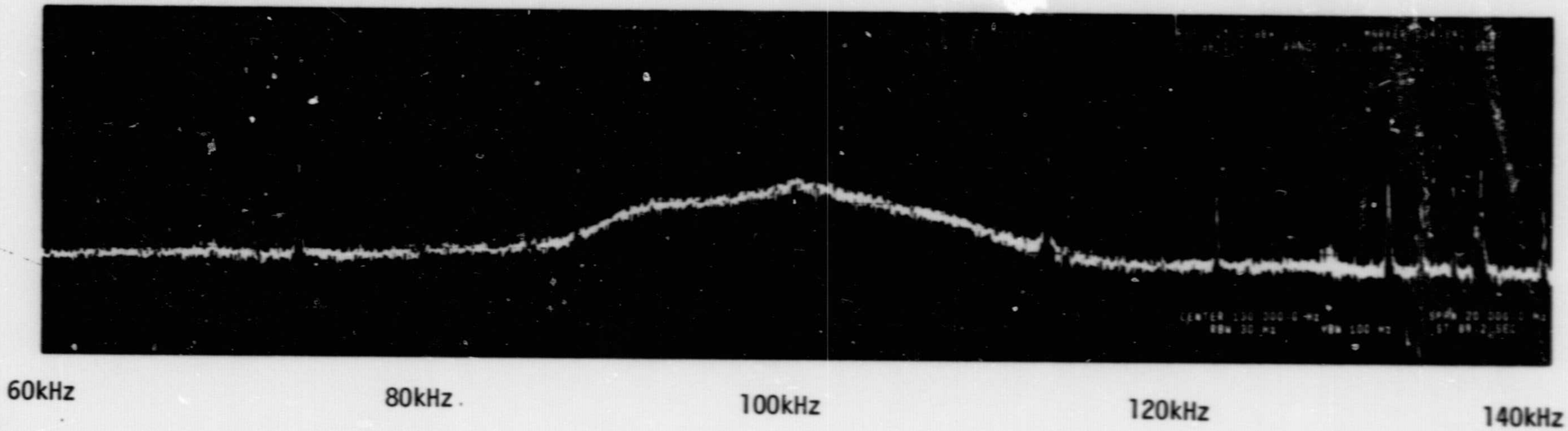


FIGURE A-4. LORAN-C SPECTRUM AT THE BURLINGTON VT AIRPORT

chains. All of the stations in the Northeast U.S. chain are dual rated. Within the existing U.S. chains, GRIs for adjacent chains are chosen to make cross chain interference negligible. Continued careful selection of GRIs for additional chains should keep cross-chain interference from becoming a problem.

The final signal quality parameter is skywave contamination. The skywave typically arrives from 35 to 50 microseconds after the groundwave signal. Within the U.S. coverage areas for LORAN-C, a properly operating receiver locked onto the third cycle should experience no problems due to skywave contamination. Thus, skywave interference is assumed here to be negligible within the National Airspace System (NAS), and negligible in the State of Vermont.

APPENDIX B

LOW COST LORAN-C RECEIVER STUDY RESULTS

The FAA has sponsored a low cost general aviation receiver design study, reported in Reference 5. The result of that study is a set of recommendations for a receiver meeting minimum operational performance standards. These recommendations are taken as the baseline receiver performance characteristics.

As a result of tradeoff analyses, the low-cost receiver was selected to have the relevant characteristics summarized in Table B-1. Additional design parameters recommended in Reference 5 for this receiver are listed in Table B-2. Some of the implications of these minimum operational performance standards as they affect ground-based testing requirements, are as follows:

1. Automatic tracking of two chains with up to five stations per chain, along with capability for master independent operation, provides automatic backup navigation capability transparent to the user.

2. Predicted receiver TD jitter of 150 nanoseconds (one sigma) at SNR = -10 db, combined with predicted propagation secondary phase correction accuracy of 250 ft. (one sigma), conforms to AC90-45A approach specifications.

The airborne user will require the LORAN-C navigation system to meet a number of operational criteria, including:

1. Consistency of position fix after station changes:

   - Traversing from one triad to another within a chain
   - Traversing from one chain to another
   - Entering near-field of transmitters
   - Backup operation (both in-chain and cross chain)

TABLE B-1. LOW-COST RECEIVER TRADEOFF RESULTS

CHARACTERISTICS	RECOMMENDATIONS
Antenna Type	Dual E-Field
Antenna Couplers	Wideband
Position Determination Technique	Hyperbolic
Chains Tracked	Two, with cross-chain fix capability
Stations Tracked	Up to five per chain
Propagation Compensation	Encoded conductivity table; use Millington's Method.
Master Dependency	Master independent operation after master outage
Interference Filters	Two fixed (88 & 115.3 kHz)

TABLE B-2. RECEIVER PERFORMANCE PARAMETERS

PARAMETER	VALUE
Receiver Sensitivity	<10 μv
Signal to Noise Threshold	
- Acquisition	-10 db
- Track	-14 db
No. of Stations tracked simultaneously	10
Minimum signal level	100 μ v/m
Dynamic Range	90 db
Secondary Phase Correction Accuracy	250 ft (Rms)
Near Field Avoidance Range	10 nm

2. Receiver must be able to always choose the correct latitude and longitude solution for each TD pair.

3. Separation minimums must be maintained between aircraft using different chains in overlapping coverage areas.

4. Probability of undetected cycle slip (locking onto the wrong RF cycle) occurrence should be negligible.

5. No degradation in performance during heavy precipitation static (P-static) conditions.

Achieving adequate position fix consistency after station changes will require rapid and accurate on-line problem detection and isolation, as well as a consistent set of propagation corrections for all possible station combinations at the same location. Maintaining adequate separation between aircraft operating with different station combinations can also be assured by providing consistent propagation corrections. However, since the enroute accuracy requirements of AC90-45A are much less restrictive than the approach requirements, it will be assumed that enroute separation minimums will be easily maintained using LORAN-C if it can be shown that approach requirements are met.

APPENDIX C

ADDITIONAL ANALYSIS OF TWO FLIGHTS

In spite of all precautions no system is immune to failure so it is still of significant concern how a pilot should and is likely to react to a loss of navigation information. One flight during the test program experienced the failure of the Nantucket station for approximately 6 minutes. On at least one other flight several outages of much shorter duration occurred. These test flights were being conducted under VFR rules and proceded without mishap, but the circumstances of these failures indicate the need for careful study.

The primary problem concerns the information supplied to the pilot regarding the failure. This information was discovered to be delayed, confusing and contradictory. In a critical situation the pilot must know immediately that a problem exists and the nature and likely duration of the problem so that appropriate action can be taken. Changes in receiver software design could alleviate most of the problems discussed here.

During an approach to MPV made on Flight BTV 362-1, Nantucket stopped transmitting. The sequence of events that took place on this flight have been depicted (Figure C-1) in parallel time lines for each relevent measurement made.* Although the failure lasted approximately six minutes, during much of this time the TDL-711 receiver operated using the alternate triad with little significant degradation of accuracy. However, the transitions from primary to alternate triads and back to primary were lengthy and complex processes that warrant closer examination.

*It is important to note that delays between actual events, such as signal/noise drop, and the detection and measurement of these events can be significant; however the relative sequence of events in the aircraft is of critical importance to this evaluation.

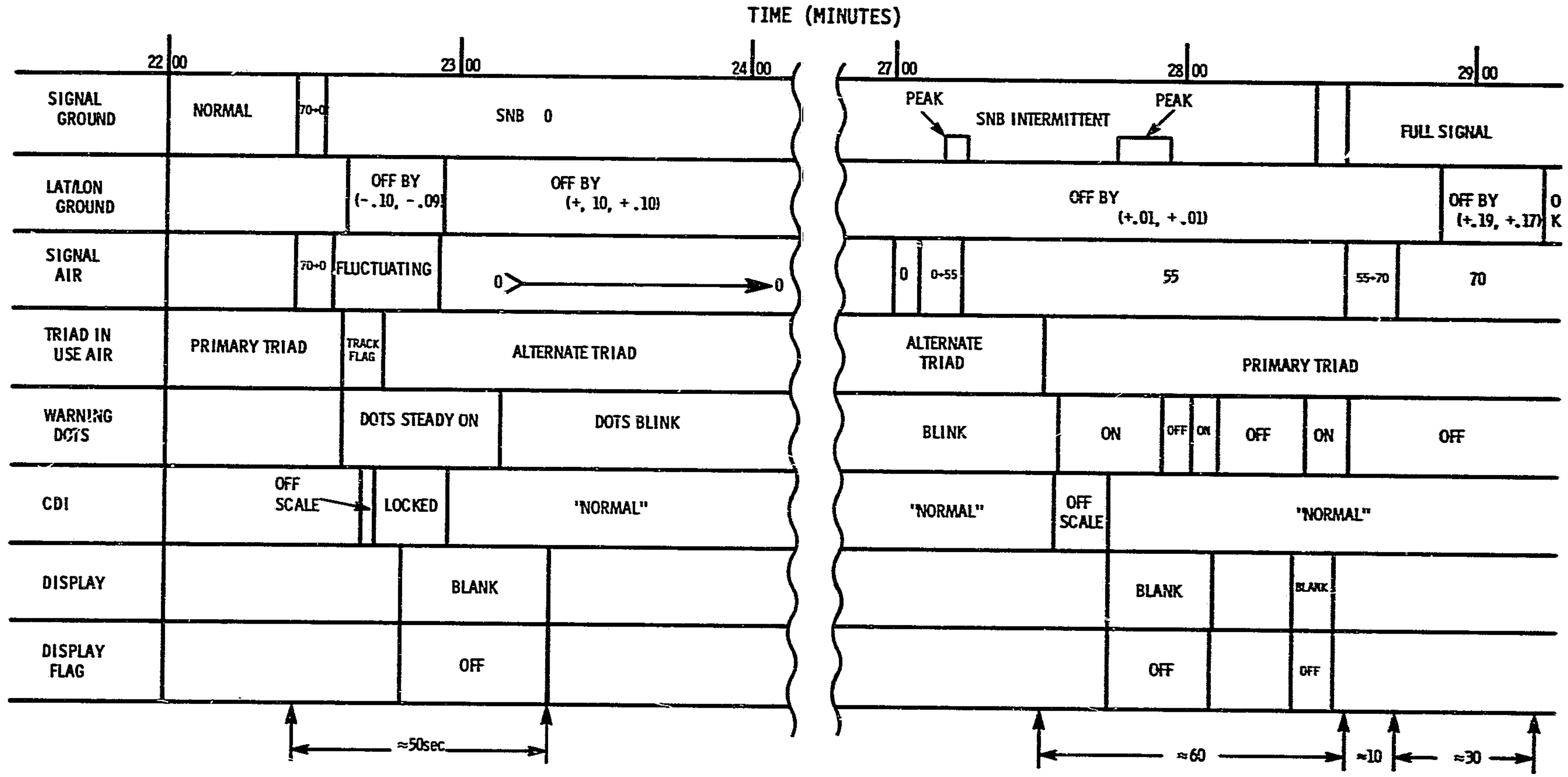


FIGURE C-1. TIMELINE OF EVENTS DURING THE OUTAGE OF NANTUCKET ON FLIGHT BTV 362-1

At 20:22:26 both air and ground recorders indicate a rapid decline in SNB (Nantucket signal/noise ratio) which subsequently remains at or near zero.* The alternate triad is used beginning 18 seconds after SNB begins to fall. If the pilot was aware within seconds that the signal was lost but that the alternate triad was in track and would be providing information momentarily he could probably have proceeded with little concern, even on an approach. However, the first indication of failure came 10 seconds after SNB dropped when the warning dots came on. Five seconds later the CDI needle jumped off the scale briefly then remained frozen approximately centered until 32 seconds from the beginning of the incident. During this period the CDU display went blank and the CDI warning flag switched on. This lasted until 52 seconds from the loss of Nantucket, when the CDI warning flag disappeared and the CDU blinking dots indicated an alternate triad was being used.

*The values used in this report to describe signal/noise are those used by the TDL-711 receiver. These signal/noise numbers correspond to the more conventional decibel scale as follows:

db	711 No.
-12	28
-10	30
-8	38
-6	42
Threshold for Acquisition	
-4	52
-2	78
0	80
+2	92
+4	E1
+6	E4

When the Nantucket signal returned and was reacquired by the system some confusion was created. At 20:27:05 the SNB recorded in the air rose rapidly from 0 to 55, somewhat lower than its earlier value of 70. The ground station indicated that for several seconds prior to, and for more than a minute following this, SNB was intermittent but always less than half of its prior level. This may have been a problem with the equipment on the ground because the airborne equipment did switch back to the primary triad soon after this. Within 2 seconds of switching back to the primary triad the warning dots stopped blinking and went on continously for 22 seconds; and the CDI needle swung off the scale for 11 seconds.

The CDI warning flag appeared and the display blanked during the time the dots were on and continued beyond the time the dots were off. Next, before the display was restored the dots came on again for 5 seconds. When everything finally appeared normal 35 seconds had elapsed since triad switchover. The system settled down 25 seconds later when SNB rose from 55 to 70, but before this the dots came on for one more period of 9 seconds and the screen blanked for 8 seconds. For a full minute there was doubt as to the reliability of the navigation information available. It appears that the triad switch occurred following the initial SNB rise but should have waited for the more reliable signal which followed more than a minute later.

This performance would have required an immediate missed approach under actual IFR conditions. The indications of trouble should be made more timely and consistent, the alternate triad should continue to be used until a strong signal has returned and steps should be taken to reduce the transition time from one triad to another. (However, if this transition had occured in the enroute environment, it would be no more critical than overflying a VOR station).

Several additional incidences during this flight are also interesting. Twice the ground station reported drops in signal to noise of the master with corresponding lapses in position information. The warning dots were displayed after 9 and 7 seconds repectively and turned off following the return of signal strength. However, the dots appeared at two other times staying on for 14 and 22 seconds repectively when no S/N drop was indicated at either the

ground station or by the airborne equipment. These indications correspond to a leg change point, which required a turn of approximately 140 degrees. Due to the accelerations experienced during this turn, the receiver may have been unable to converge on a position fix. Earlier test have indicated that turns of 3 degrees/sec and 6 degrees/sec do not cause an unlock condition to occur indicating the accelerations experienced here were much higher than would normally be found during instrument operations.

Assuming the pilot had reliable status data, alternatives could be specified and executed when called for. These range from switching to an alternate triad to switching to a backup navigation mode. If use of an alternate triad is possible without recalibration then this will be the first choice. During the final phases of an approach this switch might be cause for increased minimums or even a missed approach to permit a new calibration value to be entered. Should the alternate triad not be available, then an alternative form of navigation should be used.

There was one occasion during the Vermont flight test program while operating with the primary triad when a momentary transmitter outage caused the TDL-711 to indicate that a calibration was required. The flight was BTV 355 and the relevant events of this flight are summarized in Table C-1.

Prior to flight 355 the need for a calibration was indicated and one was performed while on the ground. Corrections of 1.438' south and 1.29' east were required. Subsequently, an approach was made to BTV RW15 to validate this calibration. The course flown was observed to be approximately 1/4 nm left (northeast) of centerline. With the calibration removed a second approach also proved to be unsatisfactory. An air calibration was then performed over the threshold of the runway. Corrections of 1.4' south and 1.2' east were used. These are quite similar to the values found during the ground calibration.

An approach at MVL was flown and again a 1/4 nm crosstrack error to the east was observed. A third calibration conducted while over the MVL runway threshold resulted in values of 1.1' south and 0.3' west. This calibration proved to be accurate for approaches to Montpelier RW17 and Burlington RW15.

TABLE C-1. SEQUENCE OF SIGNIFICANT EVENTS ON FLIGHT 355

CALIBRATIONS	APPROACHES	MOMENTARIES	TIME
		Caribou off air cycle slip on Nantucket occurred (10 ms):	14:51
Ground Calibration entered:			15:02:56
Ground Calibration deleted:			15:07:25
	First Approach to BTV (poor):		15:30
		Master Off Air:	15:44:28
Air Calibration over MAP @ BTV:			15:49:13
	Approach to BTV:		15:49:13
		Master Off Air Cycle slip ACK corrected Caribou slipped (10 ms):	15:50:45
Air Calibration deleted:			15:52:33
	End approach MVL (poor):		16:16
Air Calibration:			16:36:19
	Approach MVL (excellent):		16:44
	Approach MPV (excellent):		16:56
	Approach BTV RW15 TSCT =180ft: (visual)		17:16

Upon returning to the ground surveyed point at BTV and recalibrating, corrections of .238' south and .21' west were measured -- confirming the last air calibration.

Follow up investigation indicated that there may have been momentary difficulties with the transmitters during the calibrations. A brief drop in SNA was recorded both on the ground and in the aircraft during the period when the receiver was attempting to lock onto the signals. The USCG station log confirmed this momentary at Caribou, ME. When signal lock finally occurred the envelope status of B (Nantucket) was much lower than normal (approximately 30 to 40). The ground calibration was made following this and the TDB found to be 10.6 microseconds in error. Apparently, a cycle slip had occurred since this time corresponds to one cycle.

This cycle slip condition continued until the second momentary experienced by the master station around 15:51. While relocking, following this momentary, the cycle slip on the Nantucket signal was corrected; however, just prior to this the tracking of the Caribou station slipped one cycle. It is interesting to note that the earlier momentary around 15:44 did not stimulate any slippage or correction of slippage; this may be due to the shorter duration of that event.

During both cycle slips the corresponding envelope numbers were significantly different from their usual values. Although recordings of the precise signal characteristics during this period are not available, it is likely that they were distorted in some way that made it difficult for the receiver to lock on properly. However, the dramatic shifts in envelope numbers should have provided an indication to the tracking software that a problem existed.

The incident indicates that momentaries can cause cycle slip under certain circumstances which indicates the need for further study of this phenomenon. However, procedural solutions to this problem could prove to be adequate. A calibration value as large as the one required should be an indication to the pilot that a problem may exist -- particularly following a momentary.

Operating procedures should call for resetting the receiver and allowing it to relock before entering a calibration. In addition, the warning dots or display flag should be triggered when envelope numbers are out of tolerance to notify the pilot of the possible malfunction.

An additional malfunction was observed during the analysis of this flight which can be corrected through software modifications. The first two calibrations entered on the ground and inflight should have compensated for the cycle slip condition as long as it remained constant. However, the ground calibration did not appear to suffice during the first approach to BTV.

Upon closer examination it was determined that the calibration values entered prior to takeoff had been erased. This occurred again following the airborne calibration. In both cases, events prior to the deletion were similar, indicating a possible explanation. Table C-2 is a list of the events surrounding these deletions. As seen here, after the calibration had been completed the pilot began entering a waypoint definition. In both cases, however, he began entering the latitude and the longitude of the waypoint while in TD mode. Noticing the error before completing the entry he switched to L/L mode before erasing the erroneous data. Apparently, rather than clearing the incomplete TD fields, the area calibration contained in waypoint zero was deleted instead.

Modifications should be made to eliminate this potential source of error. A light indicating that a calibration is in use would also be helpful since it would have prevented this problem and would also warn a pilot that an earlier calibration was still present even though the need for it had passed.

The difficulties experienced with area calibration strengthen the argument that all calibration values should be stored in the computer and used automatically. Since negligable time variation in grid bias has been measured, and since a single calibration value for each triad is valid over a wide region, permanently stored values are clearly the best choice.

TABLE C-2. EVENTS SURROUNDING THE DELETION OF AREA CALIBRATION VALUE ON FLIGHT 355

Calibration:	
Switch to enter mode (L/L):	15:00:23
Set to W/P 0:	15:00:28
Enter L/L and switch to TD:	15:01:16
Complete TD entry, switch to L/L to check:	15:03:18
Complete check, switch to Dist/Brg mode:	15:05:56
Switch to TD mode:	15:06:04
Enter W/P:	
Switch to enter mode (still in TD):	15:06:27
Set to W/P 1:	15:06:29
Enter data (mistakenly) Switch to L/L:	15:07:20
WPO deleted:	15:07:25

<u>Second Example (Final Steps)</u>

Switch to enter mode	
(still in TD):	15:51:59
Enter data (mistakenly)	
Switch to L/L:	15:52:27
WPO deleted:	15:52:33

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